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Production of Nitric Monoxide Using Pulsed Discharges for a Medical Application

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Abstract—Nitric monoxide (NO) is widely used in medical treatment of acute respiratory distress syndrome (ARDS). The production of NO is of interest to the medical community. In the present work, NO is generated by pulsed discharges between two rod electrodes in a mixture of nitrogen and oxygen. An arc discharge having a temperature of about 10 000K was produced, which was sufficient to generate NO. Some of the important parameters affecting the production of NO have been investigated. These include the percentage of O₂ (6–94%) in the mixture of N₂ and O₂, the energy of the discharge (0.5–12 J/pulse), the pulse repetition rate (0.5–4.5 pps) and the flow rate (1.35–5.4 l/min) of the gas mixture. NO₂ produced in the discharge was successfully changed to NO using a heated molybdenum tube. NO₂ must be extracted from the gas before clinical inhalation. The concentration of ozone was completely eliminated by bubbling the gas mixture through water. A maximum of NO and a minimum of NO₂ concentrations were generated when the proportion of O₂ in the gas mixture was in the range of 20–27%. The concentrations of NO and NO₂ increased with increasing pulse repetition rate and with decreasing flow rate of the mixture. In all cases, NO₂ was effectively removed using a heated molybdenum tube.

Index Terms—Acute respiratory distress syndrome, medical application, nitric monoxide, pulsed arc discharge.

I. INTRODUCTION

RECENTLY, Nitric monoxide (NO), which is known to be a toxic gas, has been used in the medical community because it has a relaxing effect on the blood vessels [1]. For example, a disease of the lung that includes the acute respiratory distress syndrome (ARDS) has a high death rate of about 50%. It is being cured by inhalation of NO (iNO) [2],[3]. Fig. 1 shows a patient under medical treatment for ARDS with all accessory equipment including the gas analyzer which detects NO and NO₂, the NO gas cylinder, the mixing of O₂ and air, the humidifier and the water trap [4]. This is a complex arrangement and a more suitable and safe device to inhale NO is required. Many doctors are currently using an industrial cylinder of NO to provide iNO [5]. However, an industrial cylinder might be risky if a leak is present, since it would generate NO₂ by mixing NO

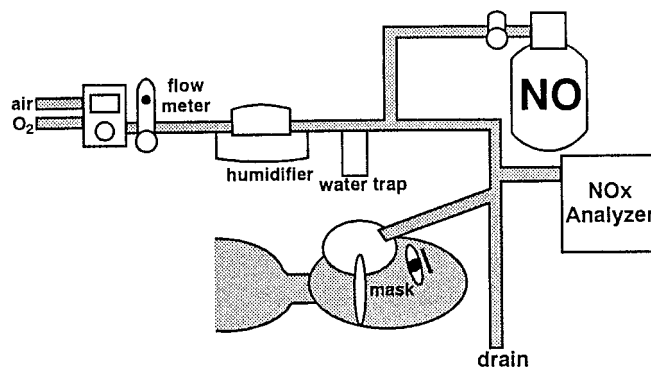


Fig. 1. Equipment for supplying NO to a patient under medical treatment for ARDS.

with O₂. The toxic effects to the lungs of NO₂ at high concentrations are well known [4]. Therefore, a device to ensure a safe inhalation of NO is needed for many patients who have a lung disease. A production of NO using a gliding arc was reported by Richard *et al.* [6]. However, dc applied voltage was employed and only air at atmospheric pressure was considered.

In the present work, the purpose is to develop a safe system for the generation and inhalation of NO. A pulsed arc discharge was used to generate NO. A pulsed arc discharge has many advantages compared to dc arc. They are as follows:

- 1) the plasma temperature is higher than using dc;
- 2) the damage to the electrodes is smaller than with dc;
- 3) the pulsed discharge is more stable.

In the present experiment, the generation of NO using pulsed arc discharge was confirmed. The gas composition of O₂ and N₂, the energy of the pulse, the pulse repetition rate, and the gas flow rate have been varied in order to obtain the most suitable concentration of NO for medical applications. The pulsed arc discharge generates NO₂ with NO. Because a small quantity of NO₂ is very toxic for the patient [7], NO₂ is removed using a heated molybdenum tube.

II. EXPERIMENTAL SETUP AND PROCEDURE

Fig. 2 shows the experimental setup. The electrical circuit consisted of a dc power supply (50 kV, 0.3 mA), the charging resistance, the capacitor, spark gap switch (SGS) and a pair of brass rods as the electrodes. The brass rods had diameters of 12 mm and their ends were at a radius of curvature of 5 mm. The distance between the electrodes was 5 mm. At first, the power supply charged the capacitor. The SGS was closed by a trigger

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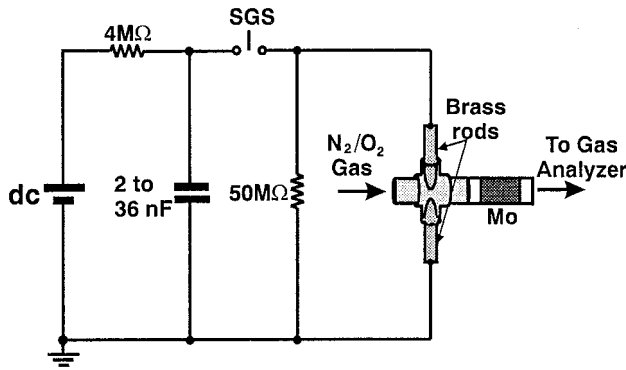


Fig. 2. Experimental setup.

pulse (15 kV), and a pulsed arc discharge developed between the electrodes. These conditions were common to 2.1. and 2.2.

A. Determination of the Plasma Temperature of the Pulsed Arc Discharge

The light emissions from the pulsed arc discharge were measured by an optical multichannel analyzer (OMA, Atagobussan, Japan). The energy of the pulse was changed by changing the capacitance from 2 to 36 nF. The dc charging voltage was constant at 25 kV. The temperature of the pulsed arc plasma was calculated using the line pair method [8]. This method uses the relative ratio of emission intensities on the plural spectrum lines. The temperature of the plasma is derived from the following equation:

$$\ln \left(\frac{I\lambda}{Ag_u} \right) = -\frac{1}{kT} E_u + \ln C \quad (1)$$

where I , λ , A , g_u , E_u , k , T , and C are the relative ratio of emission intensity, the wavelength, the transition probability, the statistical weight of the upper level, the energy of the upper level of the copper lines, Boltzmann's constant, the temperature of plasma and a constant for various atoms, respectively. The transition probabilities, the statistical weights of the upper level and the energy of the upper levels of the copper lines are shown in Table I [9].

Assuming a linear plot of $\ln(I\lambda/Ag_u)$ versus E_u , T can be calculated. The discharge electrodes were made of brass which includes copper. The four copper lines were used as the plural spectra lines. They have the wavelengths of 510.55, 515.32, 521.82, 529.25 nm. Table I shows A , g_u , and E_u for these four lines.

B. Conditions for NO Production

In Fig. 2, a molybdenum tube (internal diameter, 4.6 mm; length, 100 mm) was inserted between the chamber housing the electrodes and the gas analyzer to serve as NO₂ converter. A mixture of nitrogen and oxygen at 1.01×10^5 Pa was used at the input to the arc discharge chamber. The concentrations of NO and NO₂ were measured using the gas analyzer after a steady state was reached (within 5 min). The gas analyzer is based on the method of potentiostatic electrolysis [10]–[12]. This method relies on the characteristic reaction of oxidation

TABLE I
PARAMETERS OF THE SPECTRA OF THE
COPPER LINES [9]

Wavelength λ [nm]	Transition probability A [$10^8/s$]	Statistical weight g_u	Upper Energy level E_u [eV]
510.55	0.02	4	3.822
515.32	0.60	4	6.195
521.82	0.75	6	6.196
529.25	0.109	8	7.742

TABLE II
EXPERIMENTAL CONDITIONS, Mo, MOLYBDENUM; SS, STAINLESS STEEL

	Expt. #1	Expt. #2	Expt. #3	Expt. #4	Expt. #5
Proportion of O ₂ in the mixture of O ₂ and N ₂ [%]	6 – 93	26	26	26	26
Capacitance of capacitor [nF]	20	2 – 36	20	20	20
Pulse repetition rate [pps]	2	3	0.5 – 4.5	2	2
Gas flow rate [l/min]	1.5	1.5	1.5	1.35 – 5.4	1.5
Temperature of Mo and SS [K]	298	298	298	298	298 – 873
Charging dc voltage [kV]	22	25	22	22	22

and de-oxidation of the surface of an electrode immersed in an electrolyte solution. The current which is measured at a constant applied voltage gives a measure of the gas concentration. Different voltage is applied for measuring NO and NO₂. In the present work, the electrode was made of gold and the electrolyte was sulfuric acid. The instrument (testo 33) is calibrated by the manufacture (Hodakatest, Japan).

The proportion of O₂ in the mixture of O₂ and N₂ was changed from 6 to 93%. The energy of the pulse was changed by changing the capacitance from 2 to 36 nF. The charging voltage was constant at 25 kV. The pulse repetition rate was changed from 0.5 to 4.5 pps (pulses per second). The flow rate was changed from 0.9 to 5.4 l/min. The temperature of molybdenum was changed from 298 to 873K in order to study the effectiveness of molybdenum on the removal of NO₂. A stainless steel tube, having the same dimensions as for the molybdenum, was also used but found to be ineffective. Table II shows the conditions of the experiment. In each column only one parameter is varied while all others remained constant. Five different experiments, as shown in Table II, were performed.

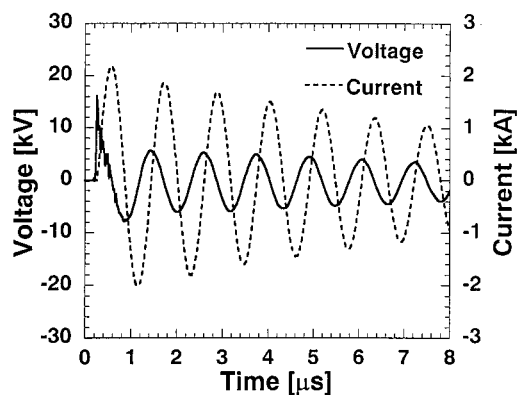


Fig. 3. Typical waveforms of the applied voltage and the discharge current.

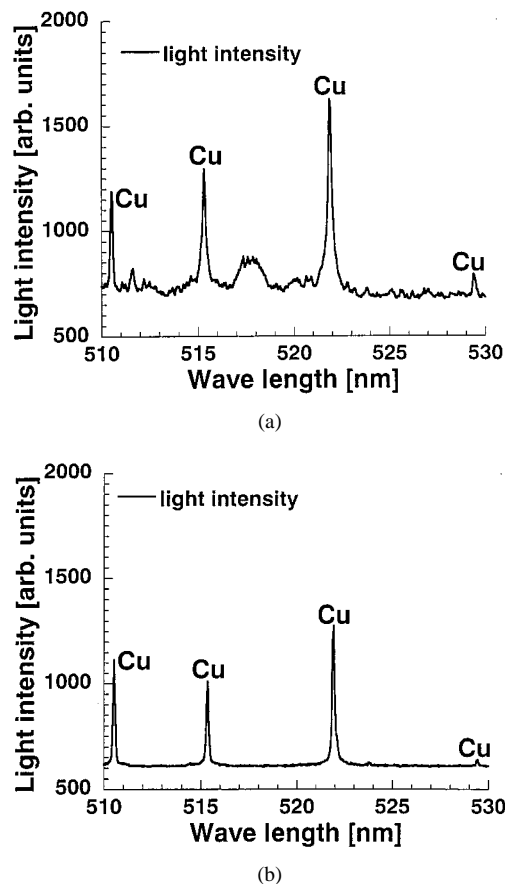


Fig. 4. Four copper spectra lines using two different capacitances (a) 2 nF and (b) 36 nF, at a charging voltage of 25 kV.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Characteristics of the Pulsed Arc Discharge

Fig. 3 shows typical waveforms of the applied voltage and the discharge current between the electrodes. Both waveforms oscillated after applying the trigger voltage. Fig. 4(a) and (b) show the four copper spectra lines using 2 and 36 nF, respectively. These four copper lines were obtained in all capacitance values (2–36 nF).

Fig. 5 shows a plot of $\ln(I\lambda/Ag_u)$ versus E_u for different applied energy ($C = 2$ to 36 nF). The straight-line approximation using (1) is used to get an approximate gas temperature,

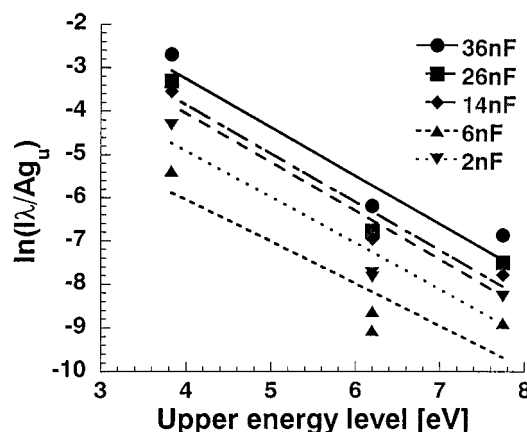


Fig. 5. Dependence of $\ln(I\lambda/Ag_u)$ on E_u as a function of capacitance at charging voltage of 25 kV.

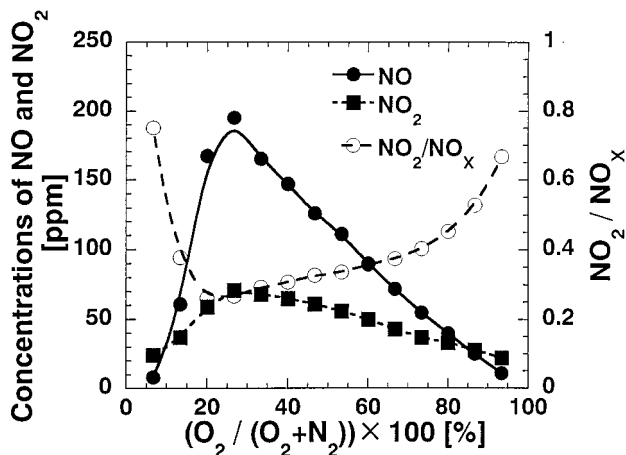


Fig. 6. Concentrations of NO, NO₂, and the ratio of NO₂/(NO + NO₂) as a function of $(O_2/(O_2 + N_2)) \times 100$ [%], under the experimental conditions of expt. #1 in Table II.

even though the data points deviate from the straight line. It can be seen from Fig. 5 that the straight lines for different capacitors are of the same slope. The gas temperature was found to be about 10 000 K. This temperature is sufficient to generate NO, since the mixture of N₂ and O₂ is transformed to NO at gas temperatures above 1000 K.

B. Characteristics of NO Production

Fig. 6 shows the concentrations (in parts per million, ppm) of NO, NO₂ and the ratio of NO₂/(NO + NO₂) as a function of $O_2/(O_2 + N_2)$. It should be noted that $NO_X = NO + NO_2$. It is desirable that the ratio of NO₂/NO_X should have a low value. It can be seen from Fig. 6 that the concentrations of NO and NO₂ had peaks when the proportion of O₂ in the mixture was about 26%. At this ratio the value of NO₂/NO_X was also the lowest. For medical applications, this result is very desirable because a largest amount of NO combined with the lowest value of NO₂/NO_X was generated.

Fig. 7 shows the dependence of the concentrations of NO, NO₂, and NO₂/NO_X on the capacitance and therefore on the energy of the pulse (charging voltage was constant at 25 kV). The concentrations of NO and NO₂ increased with

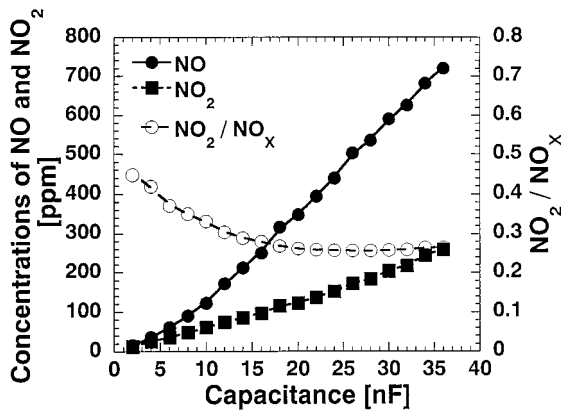


Fig. 7. Dependence of concentrations of NO, NO₂, and NO₂/NO_x on the capacitance, under the experimental conditions of expt. 2 in Table II.

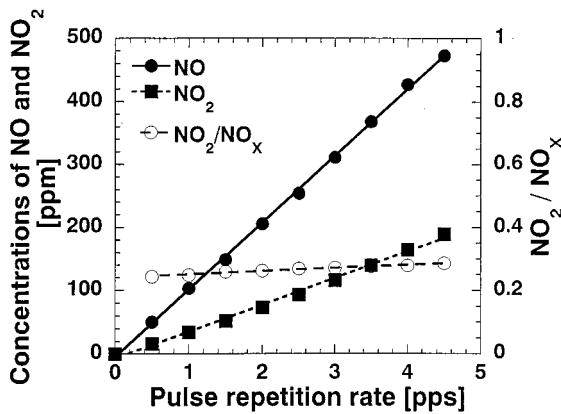


Fig. 8. Concentrations of NO, NO₂, and NO₂/NO_x as function of the pulse repetition rate, under the experimental conditions of expt. #3 in Table II.

increasing the value of the capacitance and therefore of the energy of the pulse. The value of NO₂/NO_x decreased with increasing the value of capacitance up to 20 nF and thereafter remained constant. Fig. 8 shows the concentrations of NO, NO₂, and NO₂/NO_x as function of the pulse repetition rate. The concentrations of NO and NO₂ are in direct proportion to the repetition rate. Concurrently, the value of NO₂/NO_x was constant at each repetition rate. The measurement at 0 pps (Fig. 8) was taken when high voltage pulses were not applied to the mixture of N₂ and O₂. Fig. 9 shows the concentrations of NO, NO₂, and NO₂/NO_x as function of the gas flow rate. The concentrations of NO and NO₂ decreased with increasing the gas flow rate. Concurrently, the value of NO₂/NO_x was constant at 0.25 in the range 1.35 to 5.40 l/min.

Fig. 10(a) shows the concentrations of NO, NO₂, and NO₂/NO_x as function of the temperature of molybdenum. Fig. 10(b) shows the concentrations of NO, NO₂, and NO₂/NO_x as function of the temperature of stainless steel. In the case of molybdenum, the concentration of NO increased and that of NO₂ decreased with increasing the temperature of molybdenum starting from about 720 K. However, in the case of stainless steel, NO and NO₂ concentrations were constant in the range 298–873 K [Fig. 10(b)]. It is evident that the concentrations of NO increased and that of NO₂ decreased due to the presence of molybdenum. With molybdenum, NO₂

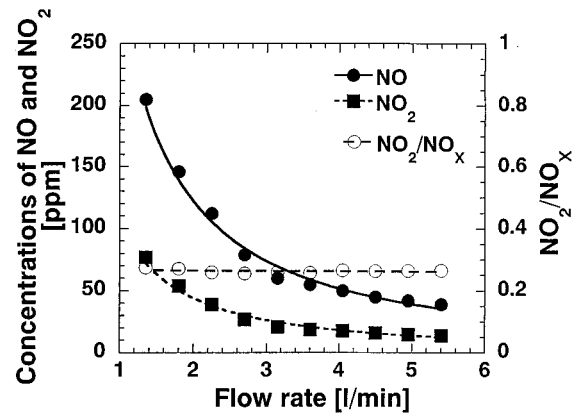
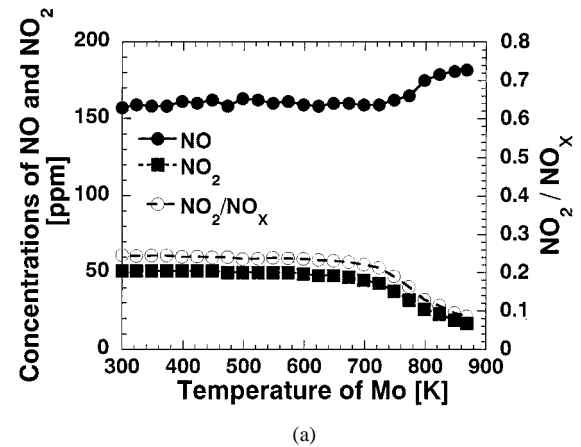
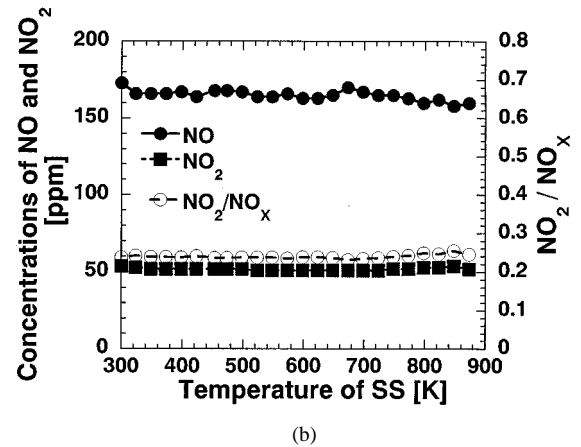


Fig. 9. Concentrations of NO, NO₂, and NO₂/NO_x as function of the flow rate, under the experimental conditions of expt. #4 in Table II.



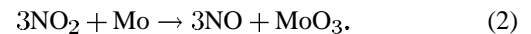
(a)



(b)

Fig. 10. Concentrations of NO, NO₂, and NO₂/NO_x as function of the temperature of (a) molybdenum (Mo) and (b) stainless steel (SS), under the experimental conditions of expt. #5 in Table II.

is converted to NO because the decrease in NO₂ matched the increase in NO. NO₂ was converted according to the reaction [13]



The concentration of ozone which is produced in the arc discharge was measured with the instrument available in the laboratory (Ebara Jitsugyo co., model DOA300). This instrument relies on the absorption of ultraviolet (UV) at 235.7 nm where

the absorption cross section is highest. For conditions necessary to obtain the suitable concentrations of NO for medical applications (proportion of O₂ in the mixture = 26%, capacitance = 20 nF, pulse repetition rate = 4.5 pps, gas flow rate = 2.0 l/min and charging dc voltage = 22 kV), the concentration of ozone was measured to be 10 ppm. This concentration might be sufficient to cause lung disease [14], [15] and therefore it must be removed. It was possible to remove completely the ozone in the mixture by bubbling it through water with negligible changes in the concentrations of NO. This was done and the concentration of ozone was found to decrease from 10 to 0 ppm.

IV. CONCLUSION

Production of nitric monoxide using pulsed discharges was studied for medical application. The results are summarized as follows:

- 1) NO was produced using pulsed arc discharge at a gas temperature of about 10 000 K.
- 2) NO₂ was largely removed using heated Mo at 870 K.
- 3) To obtain the highest concentration of NO, the proportion of O₂ of about 26%, the capacitance value as large as possible (36 nF), the pulse repetition rate as high as possible (4.5 pps) and the gas flow rate as low as possible (0.5 l/min) are necessary.
- 4) The concentration of ozone can be completely eliminated by bubbling the gas mixture through water.

The productions of NO using air, and the detail measurements of gas composition following discharges therein are the subject of a future study. This method of production of NO using pulsed arc discharge in air will be tested using animals.

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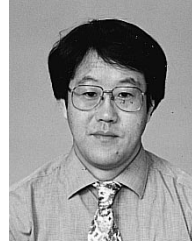
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