THE REACTION CHARACTERISTICS OF NO AND SO_2 IN THE DIELECTRIC BARRIER DISCHARGE PLASMA PROCESS

by

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Many factors affect the reaction characteristics of nitrogen oxides and SO_2 in a dielectric barrier discharge reactor. Changing the SO₂ initial concentration, oxygen content and water vapor content to study the reaction mechanism of NO and SO₂ in the dielectric barrier discharge plasma process has been conducted. It was shown that the initial concentration of SO_2 varied in a larger scope has little effect on the reaction characteristics of NO and SO₂ in the $N_2/SO_2/NO$ system. Increasing the water vapor content in the $N_2/NO/SO_2/HO$ system would reduce the concentration of SO_2 significantly in the flue gas, and the influence on SO_2 is more obvious than on NO. Then, the influence of oxygen on the reaction characteristics of SO_2 is not obvious, increasing the O_2 concentration in the $N_2/NO/SO_2/O_2$ system, the changed of SO_2 concentration is less than 10%. But the adding of O_2 affects the reaction of NO in the dielectric barrier discharge process obviously, it can promote the conversion of NO_2 and other NO_{w} at the same time, the generation of NO was also being accelerated under certain conditions. By analyzing the reaction mechanism, it was found that the activated radicals produced in the dielectric barrier discharge process concerned SO₂ reaction mainly OH, while related the reaction of NO, the O and N play an important role. Through the experiment and analysis, it was also deduced that there are oxidation and reduction reactions existed at the same time, also the generation and removal of NO occurred simultaneously.

Key words: dielectric barrier discharge, reaction mechanism, activated radical, NO, SO₂

Introduction

Non-equilibrium plasma discharges have been a hot topic of research in recent years in the field of contaminant treatment [1-5], including electron beam, corona and dielectric barrier discharges (DBD) which is a gas discharge with an insulating medium inserted into the discharge space. This discharge is very uniform, diffuse and stable, and can work in a wide

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range of pressure that is from 10^4 - 10^6 Pa and frequency that is from 50 to 10^6 Hz. Although this kind of discharge has been developed and applied more widely, the research on it has only been in the past two decades. So far, there is no complete mechanism analysis of nitrogen oxides and SO₂ in DBD, which cannot be analyzed completely, because there are many possible mutual reactions among N, O, water vapor, nitrogen oxides, and SO₂, and the current reaction rate of many reactions is unknown. Also, in the system, in addition to atoms and ionic groups, the excited states of all atoms, molecules and positive and negative ions are also taken into account. Therefore, a complete mechanistic analysis of the reaction must include the interactions between these species. Matzing [6] listed more than 700 discharge reactions in flue gases. Kossyi *et al.* [7] gave more than 80 reactions in the nitrogen/oxygen system alone.

Much work has been done in this [8-11], mostly numerical simulations [12-14], suggesting that the main possible reaction channels for NO and SO_2 in non-equilibrium plasmas are:

- Electron dissociation of oxygen produces many oxidising substances, including ozone, which then oxidises SO₂ to SO₃ and eventually to sulphuric acid with water.
- Electron dissociation of nitrogen to produce reducing substances such as N atoms, which reduce NO to N₂.
- Electron dissociation of water produces OH *etc*. that reacts directly with nitrogen oxides and SO₂.

This manuscript mainly discusses and analyzes the reaction mechanism of NO and SO_2 in DBD through experiments in which different oxygen content, water vapor content and SO_2 inlet concentration are selected. This manuscript discusses the reaction mechanism based on the product and has an in-depth understanding of the mechanism, which is helpful to optimize the process by selecting the power source, reactor structure, *etc.*, and the reaction product can be controlled by changing the flue gas composition.

Experiment and methods

The experimental system is shown in fig. 1. The test was carried out at atmospheric pressure and room temperature, and a total flue gas flow rate of 5 lpm and an initial NO concentration of 500 ppm in the mixed flue gas were selected. There are two nitrogen inlet channels, one of which is to enter the gas mixing cylinder with other mixed gases, and the other is to pass through the water bath heater, carry the water vapor whose amount is controlled by the temperature of the water bath heater required in the experiment to mix with other gases and enter the reactor. The concentration of flue gas components entering and exiting the reactor was measured online using the 350 pro flue gas analyzer produced by Testo.

The experimental power supply is an AC high-voltage power supply. The voltage range is from 4.5-6.5 kV and the frequency range is from 5.5-7 kHz. The current and voltage waveforms is recorded with a digital oscilloscope (Tektronix, TDS2024), and the power is calculated by Lissajous [15].

The length of the DBD reactor is 500 mm, and there is a stainless steel rod with a diameter of 34 mm as a low-voltage electrode inside it. The medium tube, which is wrapped by a layer of 300 mm stainless steel mesh that is used as a high-voltage electrode, adopts co-rundum with a thickness of 2 mm and a diameter of 40 mm.

The change rate of NO and SO₂ concentration in this paper is defined:

$$\eta_M = \frac{C_{\rm in} - C_{\rm out}}{C_{\rm in}} \times 100\% \tag{1}$$

where C_{in} [ppm] is the inlet concentration and C_{out} [ppm] – the outlet concentration. Subscript M can be NO, SO₂ or NO₂. When η is a positive value, it means that the outlet concentration is less than the inlet concentration, and the systemic reaction is a removal reaction. On the contrary, when η is a negative value, it means that the outlet concentration is greater than the inlet concentration, and the systemic reaction reaction is greater than the inlet concentration, and the systemic reaction reaction.



Results and discussion

Influence of the inlet concentration of SO_2 on the reaction of NO and SO_2

In the experiment, the concentration of NO was kept at 500 ppm, and the concentration of SO₂ was taken as 0 ppm, 460 ppm, 987 ppm, and 1507 ppm. Figure 2 is a graph showing the influence of SO₂ initial concentration of NO and NO₂ concentration variation. It can be seen from the figure that as the initial concentration of SO₂ in the NO/SO₂/N₂ system increases, the removal rate of NO decreases slightly. Similarly, the SO₂ concentration changes from 460 ppm to 1507 ppm, and the reduction in NO removal rate is not large, within 10%. When the system does not contain SO₂, the NO removal effect is the best. The NO removal rate increases as the discharge power increases, and the maximum NO removal rate can reach 93.99%. Under the discharge power of 79.64 W, the NO removal rate corresponding to the initial SO₂ concentration of 0 ppm, 460 ppm, 987 ppm, and 1507 ppm are 65.53%, 41.64%, 40.79%, and 36.48%, respectively. This means that the NO removal rate decreases relatively quickly when the initial SO₂ concentration is from 0 to 460 ppm and the decrease gradually becomes smaller if the SO₂ content is increased. Therefore, after SO₂ already exists in the system, the change in concentration has little effect on the removal rate of NO. Also, in the SO₂/NO/N₂ system, the amount of NO₂ generated is very small and the change is within 2%.

In the SO₂/NO/N₂ system, the removal rate of SO₂ is relatively low and the highest is less than 15%. As the concentration of SO₂ increases, the removal rate is reduced. As shown in fig. 3, at different concentrations of SO₂, the SO₂ removal rate increases with the increase of discharge power. Moreover, when the discharge power is greater than 80 W, The SO₂ removal rate at inlet SO₂ concentrations of 460 ppm has the highest growth rate, compare that to others. When the inlet concentration of SO₂ is 460 ppm, 987 ppm, 1507 ppm, and the

power is 79.64 W, the removal rate of SO₂ is 3.48%, 3.25%, and 3.19%, respectively. Experiment shows that changes in the concentration of SO_2 within a relatively large range have basically no effect on the removal of NO and SO₂ and the production of NO₂.



of NO and NO₂ concentration variation



Influence of the water vapor content on the reaction of NO and SO_2

In the experiment, the concentration of NO and SO2 remained constant, 500 ppm and 1000 ppm, respectively, and the voltage and frequency were changed to change the discharge power. The water vapor concentration was 0.6% (v/v), 1% (v/v), and 2% (v/v). The influences of water vapor content on the concentration variation of SO₂ and NO are shown in figs. 4 and 5.



As shown in fig. 4, the addition of water vapor has an obvious effect on the removal of SO₂ when the discharge power is small. When the power is 45.82 W, the water vapor concentration is 0.6% (v/v), 1% (v/v), and 2% (v/v), the corresponding removal rates of SO₂ are 1.37%, 11.98%, and 21.61%, respectively. With the discharge power increasing, the difference between the effects of different water vapor contents on the SO₂ removal rate gradually decreases. When the discharge power reaches 130 W, there is basically no effect. The removal rates corresponding to the concentration of 0.6% (v/v), 1% (v/v), and 2% (v/v) are 34.66%, 36.67%, and 37.78%, respectively.

However, the effect of water vapor concentration on the removal rate of NO is completely different from that for SO₂. As shown in fig.5, the effect of water vapor is not obvious when the discharge power is relatively low. When the power is 45.82 W, the removal rate of NO corresponding to the water vapor concentration of 0.6% (v/v), 1% (v/v), 2% (v/v) is 8.9%, 8.36%, and 7.56%, respectively. When the power was increased to 130 W, the NO removal rate changed significantly, which were 64.08%, 54.45%, and 48.17%. The concentration of NO₂ detected in this set of experiments is too low, so it is not shown in the figure.

Influence of the oxygen content on the reaction of NO and SO₂

Generally, the flue gas produced by combustion contains 3-5% oxygen, and some even reach 6-8% rich oxygen. The effect of oxygen on the reaction of NO and SO₂ was main-







Figure 7. the generation concentration of NO₂ under different oxygen content

ly investigated in this set of experiments. In the experiment, the concentration of NO and SO_2 remained constant, 500 ppm and 1000 ppm, respectively, and the voltage and frequency were changed to change the discharge power. The oxygen concentration was 3.6% (v/v), 6% (v/v), and 8.4% (v/v). As shown in fig. 6, the influence of oxygen on NO is more obvious than that of SO₂.

When the oxygen concentration is 3.6% (v/v), the NO concentration increases when the discharge power is less than 70 W, the NO generation rate is 15.5% when the power is 54 W, the NO concentration decreases when the power is greater than 78.6 W, and the highest removal rate reaches 25.1% when the power is 100 W. When the oxygen concentration is 6%, with the increase of the discharge power, the generation rate of NO in the system increases from 32.28% where the power is 53 W to 46.2% where the power is 100 W. The greater the oxygen concentration, the more the NO concentration increases. The increase in NO concentration when the oxygen content is 8.4% (v/v) is greater than the increase when the oxygen content is 6% (v/v). The change of different oxygen concentration does not have an obvious effect on the change of SO₂ concentration. The change of different oxygen concentration is not obvious to the change of SO_2 concentration. When the power is less than 70 W, the SO₂ concentration

of the three concentrations is almost the same. When the power increases, the SO_2 outlet concentration corresponding to different concentrations of oxygen is different, but it is also 15% within.

Compared with the $SO_2/NO/N_2/H_2O$ system, the total NO_2 outlet concentration of the $SO_2/NO/N_2/O_2$ system has increased significantly, and the NO_2 outlet concentration has

increased significantly with the increase in oxygen content. As shown in fig. 7, when the power is 85 W, the outlet concentration of NO₂ corresponding to oxygen concentration of 3.6% (v/v), 6% (v/v), 8.4% (v/v) is 15.85 ppm, 38.3 ppm, and 55 ppm, respectively.

Reaction mechanism analysis

In the flue gas, there are about 287 chemical reactions related to 39 chemical components which include electrons, positive and negative ions, atoms, molecules, free radicals, and excited atoms and molecules. A large number of studies have shown that the oxidation and removal of pollutants in the discharge process are only related to the chemical reaction of free radicals [16, 17]. Therefore, many chemical reactions related to ions can be ignored to simplify theoretical analysis.

In the SO₂/N₂/NO system, the removal of NO is related to the discharge power. The increase in power increases the NO removal rate, but the concentration of SO₂ is basically unchanged. The desulfurization rate is up to about 10%, and there is basically no NO₂ generate. The removal efficiency of NO increases with the increasing of discharge power. The reason is that electrons and N₂ molecules ionize to obtain N atoms, and N atoms have a strong reducing effect on NO but little effect on SO₂ in this system [17]:

$$e + N_2 \rightarrow N + N + e \tag{R1}$$

$$N + NO_2 \rightarrow 2NO, \ k = 9.0 \cdot 10^{-12}$$
 (R2)

$$N + NO \rightarrow N_2 + O, \ k = 5.9 \cdot 10^{-11}$$
 (R3)

The addition of water vapor can greatly improve the desulfurization effect. The reason may be that electrons with high energy and water molecules attach and react to form hydrated electrons in the ionizing electric field: $e + H_2O \rightarrow e_{aq}^-$. Hydrated electrons are a kind of free radicals with unique properties, and many chemical reactions are induced by e_{aq}^- . When the electron has energy to reach the ionization energy of O₂, N₂, and H₂O, the R4-R7 reaction occurs [18]:

$$e + H_2O \rightarrow H^- + OH + e, k = 7.2 \cdot 10^{-11}$$
 (R4)

$$H_2O + e \to H_2O^+ + e \tag{R5}$$

 H_2O^+ under goes the following decomposition and ionization reactions:

$$H_2O^+ + H_2O \rightarrow H_3O^+ + OH$$
 (R6)

$$H_2O^+ \to H^+ + OH \tag{R7}$$

This will produce active particles, such as OH, O, HO₂, *etc.*, mainly OH. Free radicals such as OH and hydrated electrons are strong oxidants. Under the condition of no absorbent and no catalyst, OH reacts with SO₂ and NO (R8-R12) to convert them into the corresponding sulfuric acid and nitric acid for removal. The experimental results show that OH has a relatively large impact on the removal of SO₂, and also has some impact on the removal of NO:

$$OH + SO_2 \rightarrow HSO_3, \ k = 7.5 \cdot 10^{-12}$$
(R8)

$$OH + HSO_3 \rightarrow H_2SO_4, \ k = 1.0 \cdot 10^{-12}$$
(R9)

$$OH + NO_2 \rightarrow HNO_3, \ k = 1.0 \cdot 10^{-11}$$
(R10)

Liu, L., *et al.*: The Reaction Characteristics of NO and SO₂ in the Dielectric Barrier ... THERMAL SCIENCE: Year 2022, Vol. 26, No. 5B, pp. 4345-4353

$$OH + NO \rightarrow HNO_2, \ k = 6.6 \cdot 10^{-12}$$
(R11)

4351

$$OH + HNO_2 \rightarrow NO_2 + H_2O, k = 0.5 \cdot 10^{-11}$$
 (R12)

Hyun Ha Kim *et al.* [19] believes that SO_2 removal is mainly through two main ways which are liquid phase process and gas phase process. The liquid phase process means that SO_2 is first dissolved in water to form HSO_3^- and oxidizes with OH and H_2O_2 in the solution to form SO_4^{2-} . The gas phase pathway means that SO_2 directly reacts with OH, HO_2 , and O_2 in the air to form SO_3 and dissolve in water. He believes that the following reactions often occur during the oxidation and removal of SO_2 in the gas phase:

$$SO_2 + OH \rightarrow HSO_3$$
 (R13)

$$SO_2 + HO_2 \rightarrow SO_3 + OH$$
 (R14)

$$SO_3 + H_2O \rightarrow H_2SO_4$$
 (R15)

The (R13) can often be carried out quickly and effectively in a humid smoke environment. Compared with other particles (O, O_3 , HO₂), OH particles have a larger reaction rate constant during the oxidation of SO₂. Therefore, the amount of OH particles has a great influence on the removal of SO₂, which means that the desulfurization rate of the reaction with high moisture content is much higher than that of the reaction with low moisture content.

After adding oxygen, the concentration of NO changes significantly. Oxygen generates a large number of oxygen atoms through the reaction of electrons with O_2 , such as $e+O_2 \rightarrow 2O+e$ This oxygen atom active group can oxidize SO₂, NO, NO₂ to higher oxides [20], such as:

$$O + SO_2 + N_2 \rightarrow SO_3 + N_2, \ k = 1.4 \cdot 10^{-13}$$
 (R16)

$$O + NO + N_2 \rightarrow NO_2 + N_2, \ k = 9.0 \cdot 10^{-12}$$
 (R17)

$$O + NO_2 + N_2 \rightarrow NO_3 + N_2, \ k = 9.0 \cdot 10^{-12}$$
 (R18)

At the same time, oxygen atoms also react:

$$O + SO_3 + N_2 \rightarrow SO_2 + O_2 + N_2, \ k = 8.0 \cdot 10^{-10}$$
 (R19)

$$O + NO_2 \rightarrow NO + O_2, \ k = 1.0 \cdot 10^{-11}$$
 (R20)

The rate constants of the two reactions (R19 and R20) are relatively large, and the oxidation rate of (R19) is greater than that of SO₂ (R16). Therefore, the removal rate of SO₂ is relatively low. Similarly, because of the occurrence of (R20), very few NO is oxidized by O to NO₂ or higher valence nitrogen oxides. Compared with the reduction reaction (R3 and R22) proceeds more slowly. However, the reaction constant of (R22) increases to $k = 1.4 \cdot 10^{-15}$ as long as the temperature reaches 400 K. Also, the excited states N(²P) and N(²D) of nitrogen atoms have rated constants of up to 10^{-11} [21], and the number of these excited state accounts for 1% of the total number of N atoms. Therefore, the concentration of NO in the system changes rapidly:

$$N+O+N_2 \rightarrow NO+N_2, k = 1.0 \cdot 10^{-12}$$
 (R21)

$$N+O_2 \to NO+O, k = 1.0 \cdot 10^{-16}$$
 (R22)

$$N+O_3 \to NO+O_2, \ k = 1.0 \cdot 10^{-16}$$
 (R23)

In summary, using the reaction mechanism of figs. 8 and 9 to summarize the reaction mechanism of NO and SO_2 , it can be seen intuitively that the removal of NO involves oxidation and reduction reactions. The oxidation reaction mainly produces NO_2 , HNO_2 , and other nitrogen oxides, and the product of the reduction reaction is mainly N_2 . The main reaction mechanisms involved in this paper are circled in the figure, with red representing reduction reaction and green representing oxidation reaction.



It can be seen from fig. 9 that there are three main ways for the reaction of SO_2 . One is that active groups such as O or HO_2 oxidize SO_2 to SO_3 , and further generate HSO_3 . This way is because the reverse reaction rate is relatively large, so the SO_2 removed through this way is very limited. The second way is to directly oxidize SO_2 to HSO_3 by OH, and then generate sulfuric acid. Comparing the experimental results, this way is the main way to remove SO_2 (Green mark as shown in figure). The third way is that SO_2 is directly dissolved in water to generate H_2SO_3 , and further oxidized to sulfuric acid. This way is suitable for flue gas with very high humidity. (The cyan marks in the figure are the first and third ways of SO_2 removal which are not suitable for this paper.)

Therefore, the chemical desulfurization and denitration process of DBD plasma depends on the concentration of active particles (such as N, O, OH, HO₂, *etc.*), whose generation and concentration depend on the average energy of the electrons in the plasma from the external electric field, the type of background gas and its high-energy electron concentration.

Conclusion

- In the SO₂/N₂/NO system, changes in the concentration of SO₂ in a large concentration range have little effect on the reaction characteristics of NO and SO₂. The main reaction is the reduction reaction of NO and N, and there is almost no formation of NO₂. The change of removal rate of SO₂ does not exceed 10%.
- In the SO₂/N₂/NO/H₂O system, the increase of water vapor can greatly improve the desulfurization effect, mainly relying on the reaction of OH and SO₂. The increase of water vapor also has an effect on NO, but it is not as obvious as on SO₂.
- In the SO₂/N₂/NO/O₂ system, the increase of oxygen has a significant effect on NO, but the change of oxygen concentration has no obvious effect on the change of SO₂ concentration. When the discharge power changes, the SO₂ concentration changes, but the range is not large, and the range is within 15%.
- According to the analysis of reaction mechanism, it is the active groups of N and O that mainly affect the reaction characteristics of NO, while the active groups OH mainly affect the reaction characteristics of SO₂.

• Further research will be carried out on other components in the flue gas, such as CO, CO₂, N₂, hydrocarbons and other NO_x, etc. Understanding the reaction mechanism of each component of flue gas in DBD with a more comprehensive analysis.

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References

- [1] Lin, H., *et al.*, Removing NOx from Flue Gas by Means of Radical Showering Incuced by DC Corona (in Chinese), *Proceedings of the CSEE*, 22 (2002), 8, pp. 150-155
- [2] Wang, Z. W., et al., The Influence of Electric Field with Discharge on the Gas Transfer Process of SO₂ (in Chinese), Proceedings of the CSEE, 26 (2006), 4, pp. 21-24
- [3] Chang, J., Recent Development of Plasma Pollution Control Technology: A Critical Review, *Science and technology of Advanced Materials*, 2 (2001), 3-4, pp. 571-576
- [4] Xu, F., et al., Study on Simultaneous Decomposition of PAHs and Dioxins in Municipal Solid Waste Fly Ashes by Pulse Corona Discharge (in Chinese), Proceedings of the CSEE, 27 (2007), 32, pp. 34-39
- [5] Wang, Z. H., *et al.*, Experimental Research for the Simultaneous Removal of NOx and SO₂ in Flue Gas by O₃ (in Chinese), *Proceedings of the CSEE*, 27 (2007), 11, pp. 1-5
- [6] Matzing, H., Chemical Kinetics of Flue Gas Cleaning by Radiation with Electrons, Adv. Chem. Phys., 80 (1991), Jan., p. 315
- [7] Kossyi, I. A., et al., Kinetic Scheme of the Non-Equilibrium Discharge in Nitrogen-Oxygen Mixtures, Plasma Sources Sci. Technol., 1 (1992), 3, p. 207.
- [8] Chang, M. B., et al., Simultaneous Removal of SO₂ and NO from Simulated Flue Gas Streams, Plasma Chem. Plasma Processing, 12 (1992), p. 565
- [9] Dahiya, R. P., et al., Plasma Chemical Investigations for NO, and SO₂ Removal from Flue Gases, IEEE Trans. Plasma Sci, 21 (1993), 3, p. 346
- [10] Jiang, X. D, et al., Kinetic Model of Non-Thermal Plasma Flue Gas Desulfurization in a Wet Reactor, Chemical Engineering Journal, 116 (2006), Feb., pp. 149-153
- [11] Li, R. N, Liu, X., Active Species Injection in Flue Gas Denitrification, *Chemical Engineering Science*, 55 (2000), 13, pp. 2481-2489
- [12] Derakhshesh, M, et al., Modeling of Hazardous Air Pollutant Removal in the Pulsed Corona Discharge, Physics Letters A, 373 (2009), 11, pp. 1051-1057
- [13] Mok, Y. S., Nam, I., Modeling of Pulsed Corona Discharge Process for the Removal of Nitric Oxide and Sulfur Dioxide, *Chemical Engineering Journal*, 85 (2002), 1, pp. 87-97
- [14] Zheng, S, et al., Modeling of the Production of OH and O Radicals in a Positive Pulsed Corona Discharge Plasma, Vacuum, 83 (2009), 1, pp. 238-243
- [15] Nagao, I., et al., NOx Removal Using Nitrogen Gas Activated by Dielectric Barrier Discharge at Atmospheric Pressure, Vacuum, 65 (2002), 3-4, p. 481
- [16] Li, R. N., Liu, X., Main Fundamental Gas Reactions in Denitrification and Desulfurization from Flue Gas by Non-Thermal Plasmas, *Chemical Engineering Science*, 55 (2000), 13, pp. 2491-2506
- [17] Mok, Y. S., Nam, I., Modeling of Pulsed Corona Discharge Process for the Removal of Nitric Oxide and Sulfur Dioxide, *Chemical Engineering Journal*, 85 (2002), 1, pp. 87-97
- [18] Bai, M. D., et al., Influence of H₂O and O₂ Content in Flue Gas on Resourcelize Desulfurizing Efficiency of Hydroxyl Radical (in Chinese), China Environmental Science, 27 (2007), 5, pp. 619-622
- [19] Ha, Kim, H., et al., The Influence of Reaction Conditions on SO₂ Oxidation in a Discharge Plasma Reactor, IEEE Transactions On Industry Applications, 37 (2001), 2, pp. 480-487
- [20] Lowke, J., Morrow, R., Theoretical Analysis of Removal of Oxides of Sulphur and Nitrogen in Pulsed Operation of Electrostatic Precipitators, *IEEE Tran. On Plasma Science*, 23 (1995), 4, pp. 661-671
- [21] Lm, C. L., Kaufman, F., Reactions of Metastable Nitrogen Atoms, J. Chem. Phys., 55 (1971), pp. 3760-3770

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