Effect of the Oxygen Concentration and Temperature on Thermal Decomposition of N₂O in an Inert Gas

Jae Geun Yun, Han Min Lee, Gwang Yeol Baik, Ji Yeop Kim, Sang Ji Lee, Min Kyu Jeon, Sang In Keel, and Jung Goo Hong*

ABSTRACT: Nitrous oxide (N₂O) is one of the greenhouse gases that contribute to global warming. But, there are few methods for controlling N₂O directly. It is essential to reduce N₂O to solve environmental problems. In this study, we investigate the O₂ concentration dependence of N₂O decomposition under an argon-based gas mixture in a high-temperature thermal reactor. The gas concentrations are calculated using CHEMKIN. The results confirm that more N₂O is converted to N₂ or NO at lower O₂ concentrations. Therefore, the conversion process is hindered by increasing the O₂ concentration. We propose a modified parameter of N₂O decomposition, and it is employed in the CHEMKIN calculations. With the modified parameter, the experimental results are in a similar tendency to the calculated results.

1. INTRODUCTION

Secondary industries based on fossil fuels emit nitrogen oxides. To minimize air pollution, the Kyoto protocol, which controls greenhouse gases, was signed in 1997. Six gases are regulated by the protocol, including carbon dioxide (CO₂), methane (CH₄), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF₆), and nitrous oxide (N₂O). Figure 1 shows the global warming potential (GWP) of N₂O and its chemical reaction in the ozone layer. N₂O has a GWP 310 times higher than that of CO₂. It causes chain reactions in the ozone layer and destroys O₃ successively. In addition, N₂O takes 135 years to be naturally reduced in the ozone layer. Nevertheless, most OECD (Organization for Economic Cooperation and Development) member countries have considerably insignificant N₂O regulations compared to those of CO₂.

There are a few methods of reducing N₂O emission from stationary sources, such as industrial incinerators or boilers. The reduction of N₂O in the exhausts can be divided into two processes: selective catalytic reduction (SCR) and selective noncatalytic reduction (SNCR). SCR can operate at lower temperatures than SNCR, but it has higher maintenance costs than SNCR due to the use of catalysts.

SNCR is a process of reducing NOₓ using a reductant without catalysts. It operates at a higher temperature than SCR, but it has a simple structure and low cost of maintenance. NOₓ from industrial machines is converted into nitrogen (N₂) and water vapor by injecting a reductant in the exhaust line at temperatures ranging from 1173 to 1373 K. As reductants, ammonia (NH₃) and urea aqueous solutions (urea solution, NH₂CONH₂) are used. A urea solution is easier to manage and cheaper than ammonia.

Figure 2 shows the decomposition mechanism and the reaction route of reductants in the SNCR process. The chemical reaction generally follows the Zeldovich mechanism, which explains the oxidation of nitrogen and the formation of NOₓ. The mechanism confirms that N₂O is formed inevitably during N₂ conversion from NOₓ. Svoboda et al. reported that N₂O formation during the SNCR process is attributed to the reductants.

Received: June 28, 2021
Accepted: October 29, 2021
Published: November 12, 2021

Figure 1. Global warming potential of greenhouse gases and the ozone layer reaction.
Amand et al. reported that N$_2$O is very sensitive to temperature, and thus, the decomposition mechanism is temperature-dependent. Kilpinen et al. reported that hydrogen cyanide (HCN) is important in the formation of N$_2$O. HCN is converted to NCO, and N$_2$O is formed by reacting NCO with NO. Kim reported that N$_2$O formation in the SNCR process decreases as the O$_2$ concentration increases. Rahman et al. reported that the temperature range for optimal NO$_x$-reduction efficiency increases as the O$_2$ concentration increases. Liu et al. reported that O radicals promote N$_2$O decomposition. Lee et al. reported that excessive residence time decreases the N$_2$O reduction efficiency.

Previous studies have shown that N$_2$O formation during NO$_x$ reduction is affected by the O$_2$ concentration. However, the dependence of N$_2$O decomposition on the O$_2$ concentration has not yet been clarified. In this study, we investigated the reduction of N$_2$O in varied O$_2$ concentrations. A laboratory-scale electric furnace was used to simulate the actual SNCR process. Thermal decomposition experiments were conducted to examine the reaction characteristics of Ar-based N$_2$O mixtures. The temperature of the reactor and the O$_2$ concentration of the mixture were set as experimental variables. Comparing experimental results with those calculated using CHEMKIN, we propose modified factors for the reaction mechanism and the rate constant of GRI 3.0.

CHEMKIN-PRO software is designed for modeling many chemically reacting flow configurations. Successful application of CHEMKIN-PRO to engineering and chemistry problems requires some basic understanding of the theory and formulations behind chemically reacting flow simulations. The CHEMKIN-PRO Theory Manual provides a broad overview of the relationships and formulations used in calculations of chemical property and source terms. It also provides brief derivations and explanations of the governing equations solved by CHEMKIN-PRO Reactor Models, as well as a discussion of numerical solution techniques and sensitivity analysis employed in the models.

GRI-Mech 3.0 is an optimized mechanism designed to model natural gas combustion, including NO formation and reburn chemistry. It is the successor to version 2.11 and another step in the continuing updating evolution of the mechanism. The optimization process is designed to provide sound basic kinetics, which also furnishes the best-combined modeling predictability of basic combustion properties.

### 2. RESULTS AND DISCUSSION

#### 2.1. Formation of N$_2$ and NO by Thermal Decomposition of N$_2$O

Figure 3 shows the variation of the calculated gas concentrations with the reactor temperature. The gas mixture is composed of 99.96% Ar, 0% O$_2$, and N$_2$O (400 ppm). The reactor temperature was varied from 1073 to 1273 K, and the residence time was fixed at 7 s. The N$_2$O concentration decreased with increasing reactor temperature. At the initial temperature (1073 K), the N$_2$O concentration was 336 ppm. N$_2$O was entirely decomposed at 1273 K. The N$_2$ concentration increased with a decrease in the N$_2$O concentration, reaching 368 ppm at a reactor temperature of 1273 K. This is attributed to the N$_2$O thermal decomposition to two N and one O components, according to eq 3 of Table 3. The two N components react again and form stable N$_2$ molecules. The NO concentration slightly increased with decreasing N$_2$O concentration. The concentration of NO was very small at the initial temperature (1073 K), but it reached 21 ppm when the reactor temperature was increased to 1273 K. This is attributed to the conversion of N$_2$O to NO, according to eq 3 of Table 3. Above a reactor temperature of 1240 K, the NO concentration was greater than that of N$_2$O. Therefore, N$_2$O thermal decomposition must be conducted under an appropriate level of temperature to avoid excessive NO$_x$ production.

#### 2.2. N$_2$O Concentration Depending on the O$_2$ Concentration

Figure 4 shows the variation of the N$_2$O concentration with reactor temperatures and O$_2$ concentrations. The calculated gas concentrations with the reactor temperature. The gas mixture is composed of 99.96% Ar, 0% O$_2$, and N$_2$O (400 ppm). The reactor temperature was varied from 1073 to 1273 K, and the residence time was fixed at 7 s. The N$_2$O concentration decreased with increasing reactor temperature. At the initial temperature (1073 K), the N$_2$O concentration was 336 ppm. N$_2$O was entirely decomposed at 1273 K. The N$_2$ concentration increased with a decrease in the N$_2$O concentration, reaching 368 ppm at a reactor temperature of 1273 K. This is attributed to the N$_2$O thermal decomposition to two N and one O components, according to eq 3 of Table 3. The two N components react again and form stable N$_2$ molecules. The NO concentration slightly increased with decreasing N$_2$O concentration. The concentration of NO was very small at the initial temperature (1073 K), but it reached 21 ppm when the reactor temperature was increased to 1273 K. This is attributed to the conversion of N$_2$O to NO, according to eq 3 of Table 3. Above a reactor temperature of 1240 K, the NO concentration was greater than that of N$_2$O. Therefore, N$_2$O thermal decomposition must be conducted under an appropriate level of temperature to avoid excessive NO$_x$ production.
The reactor temperature was varied from 1073 to 1273 K, and the residence time was fixed at 7 s. The N₂O curves were varied with the O₂ concentration in the gas mixture. For all three gas compositions, the N₂O concentration decreased with increasing temperature, but the concentration of N₂O for each temperature increased with increasing O₂ concentration. This is attributed to the conversion of N₂O to N₂ and NO with a lower O₂ concentration, following eqs 1–3 of Table 1.

### 2.3. Calculated N₂O Concentration with the Modified Parameter Constant

Figure 5 shows the variation of the calculated N₂O concentration with temperature using the GRI 3.0 and the modified parameter. O₂ concentrations of 5 and 10% were employed for each mechanism. In the case of a 0% O₂ concentration, eq 10 is considered insignificant, thus the GRI 3.0 mechanism was used for the calculation. For the modified parameter, only the value of A was varied from 1.20 × 10¹⁷ to 1.20 × 10²⁴ (cm³/gmol)/s at 5% O₂. However, both A and b were varied to 1.20 × 10²⁴ (cm³/gmol)/s and 2.0, respectively, at 10% O₂. The parameter of the GRI 3.0 mechanism was modified because it has different experimental environments and purposes. The GRI 3.0 mechanism is designed for calculating the natural gas combustion, NO formation, and reburn chemistry. The main proposal of this work is to study the thermal decomposition and reaction analysis of N₂O based on an Ar atmosphere, which is different from natural gas (CH₄). In addition, while a real combustion reaction and flow rate are fast, the gas mixture of the experiment reacts slowly because the velocity of the flow is only 10.7 cm/s. Therefore, to increase effective collisions, the values of A (a frequency or pre-exponential factor) and b (temperature proportional constant) were modified in the GRI-Mech 3.0. That is, as A in the reaction equation increases, the reaction occurs more easily. In this study, A and b values were modified to compare with actual experimental results. In addition, although modifications of the variables in eqs 1–8 were endlessly attempted, there was no significant change according to the oxygen concentration. But, in modification of eq 8, there clearly was a difference according to the oxygen concentration. For example, b and E_a were fixed, and the A value was calculated as 10¹⁷, 10¹⁸, 10¹⁹, and 10²⁰ (cm³/gmol)/s. Also, A and E_a were fixed, and the b value was calculated as −2, −1, 0, 1, 1.5, and 2. Finally, we suggest that the parameter was optimized for experimental results.

The factors of the rate constant were modified to verify the reactants or the decomposition mechanism. Comparing the calculated data, the modified parameter increased the N₂O concentration by 30 ppm relative to that of the GRI 3.0 mechanism at the same O₂ concentration and temperature.

Figure 6 shows the variation of the experimental and calculated N₂O concentrations with temperature. The compositions of the experimental gas mixture are listed in Table 1. The calculation was conducted using the modified parameter, as shown in Figure 5. The calculated results show a decrease in N₂O for all O₂ concentrations as temperature increases. The graph curve of a decreasing trend of the calculated data was similar to the experimental data depending on the O₂ concentration. In the calculations results, the conversion of N₂O to N₂ or NO increases with decreasing O₂ concentration. In the case of a 0% O₂ concentration, eq 8 is considered insignificant, thus the GRI 3.0 mechanism was used

Table 1. Elementary Reaction of N₂O (the Modified Parameter)

| reaction | k = AT^a exp(-E_a/RT) |
|----------|-----------------------|
| N₂O(+)M  <= > N₂ + O(+)M | 7.9 × 10²⁰  | 0  | 56020 |
| N₂ + O <= > N₂ + O₂ | 1.4 × 10¹⁲  | 0  | 10810 |
| N₂O + O <= > 2NO(3) | 2.9 × 10¹³  | 0  | 23150 |
| NO₂ + O <= > NO + O₂(4) | 3.9 × 10¹³  | 0  | −240  |
| NO + O + M <= > NO₂ + M(5) | 1.06 × 10²⁰ | −1.41 | 0  |
| N + NO <= > N₂ + O(6) | 2.7 × 10¹³  | 0  | 355   |
| N + O₂ <= > NO + O(7) | 9.0 × 10¹³  | 1  | 6500  |
| 2O + M <= > O₂ + M(8) | 1.20 × 10²⁴  | 2.00 | 0    |
for the calculations. At 0% O2, the N2O concentration was 336, 105, and 0 ppm at 1073, 1173, and 1273 K, respectively. The experimental results show a similar tendency with that of the modified parameter. There are intervals between the experimental values and the calculated values because of the insulation conditions and the ideal gas behavior model.

3. CONCLUSIONS

In this study, we investigated the effect of the O2 concentration and temperature on the thermal decomposition of N2O. GRI 3.0 and the modified parameter were verified by comparing the calculated and experimental results. The major findings of this work are summarized as follows:

(1) Through calculation, it was confirmed that N2O is critically affected by temperature. The N2O concentration decreases according to an increase in temperature. Also, it was confirmed that N2O molecules were converted to N2 and NO by eqs 1–3.

(2) As a result of the N2O thermal decomposition experiment according to the temperature, N2O decreases according to an increase in temperature. Also, it was confirmed that the more oxygen there is, the more it interferes with the decomposition of N2O. Higher O2 concentrations are attributed to the increase in the decomposition reaction of N2O.

(3) The calculation using GRI 3.0 showed little difference in the N2O concentration depending on the oxygen concentration, but the calculation using the modified parameters showed that the best reduction in the oxygen concentration was 0%. Therefore, with the modified parameter, the graph curve of the decreasing trend of the calculated data was similar to the experimental data depending on the O2 concentration.

(4) There was a gap between the experimental and calculated results regardless of GRI 3.0 Base and modified parameter GRI 3.0, but the difference was not important in this study. The reason for the gap was assumed to be because of the PFR model of ideal flow and heat loss from the reactor.

4. MATERIALS AND METHODS

4.1. Experimental Setup. Figures 7 and 8 show a schematic diagram and a picture, respectively, of a laboratory-scale electric furnace reactor for N2O thermal decomposition. The experimental apparatus comprises a gas supply unit, a thermal reactor, a measurement device, and an emission part. Experimental gases (Ar, O2, and N2O) flow through a mass flow controller (MFC).

The thermal reactor is a cylindrical tube (inner diameter: 114 mm; length: 750 mm) and can be heated up to 1373 K using three internal heating coils. An insulator surrounds the reactor to prevent heat loss and maintain the temperature of the experiment. The temperature of the reactor was measured using R-type thermocouples.

Here, the concentration of the exhaust gas after the reaction was measured using a nondispersive infrared (NDIR) gas meter (NOVA IR-Pro). The measurement error of the gas meter was below 2% (electrochemical sensor).

4.2. Experimental Conditions. Table 1 shows the test gas conditions for the thermal decomposition experiment. The gas mixture was composed of Ar (89.96−99.96%), O2 (0−10%), and N2O (400 ppm). The actual combustion exhaust gas was N2 and CO2. The Ar-based mixture was used to investigate the separate thermal reaction of N2O. NOx and N2O production depends on the O2 concentration and temperature. Thus, the O2 concentration of the gas mixture and the reactor temperature were varied during the experi-

Figure 6. N2O concentration according to O2 in comparison of calculation and experimental results.

Figure 7. Schematic diagram of the experimental setup (photograph was taken by Jae Geun Yun).
ment. The O$_2$-concentration dependence of N$_2$O thermal decomposition was investigated by varying the O$_2$ composition of the gas mixture at fixed residence times. The gas mixture flow rate was calculated using eq 9. In this equation, $Q$ is the gas flow rate, $D$ is the inner diameter of the reactor, $L$ is the length of the reactor, and $t$ is the residence time.

$$Q = \frac{\pi \times (D/2)^2 \times L}{t}$$ (9)

Table 2 shows the experimental conditions. Considering the normal SNCR temperature, the experimental temperature ranged from 1073 to 1273 K at a 20 K interval. For a fixed residence time of the gas mixture at each temperature, the flow rate was varied according to Charles’ law, expressed as follows

$$\frac{Q_1}{T_1} = \frac{Q_2}{T_2}$$ (10)

where $Q_1$ is the inlet flow rate, $T_1$ is the inlet temperature, $Q_2$ is the flow rate for each temperature, and $T_2$ is the reactor temperature. The concentration of the exhaust gas was measured in a 1 min interval at the rear end of the reactor after 15 min of gas supply. The numerical and graphical data reported here are the average values of 110 measurements for each experimental condition. Ambient conditions were maintained in atmospheric air (298 K, 1 atm). In high-temperature plasma, the recombination of O$_2$ atoms in the presence of a third body M is prominent. The asterisk on M in the stoichiometric equation indicates that M is energized in the reaction.

4.3. CHEMKIN Calculation Conditions. The N$_2$O thermal decomposition was simulated using CHEMKIN.$^{21}$ A one-dimensional (1D) plug flow reactor (PFR) model was employed in the simulations. The PFR model is a cylindrical reactor model that assumes a steady state during flow. The inlet gas was assumed to be perfectly mixed, therefore, continuous thermal reactions were observed inside the reactor. The furnace model has an inner diameter of 114 mm and a length of 750 mm, which is the same as the experimental setup. The temperature of the reactor was divided into 11 sections, ranging from 1073 to 1273 K. The residence time of the gas mixture was set as 7 s, considering the actual experimental conditions. The N$_2$O chemical reaction was calculated from the GRI 3.0$^{22}$ and reaction equations in Tables 3 and 4.

Table 2. Test Gas Conditions

| residence time (s) | gas composition                                      |
|-------------------|------------------------------------------------------|
| 7                 | Ar (99.96%), O$_2$ (0%), N$_2$O (400 ppm)           |
|                   | Ar (94.96%), O$_2$ (5%), N$_2$O (400 ppm)           |
|                   | Ar (89.96%), O$_2$ (10%), N$_2$O (400 ppm)          |

Table 3. Experimental Conditions

| condition         | value                                       |
|-------------------|---------------------------------------------|
| temperature (K)   | 1073–1273                                   |
| flow rate (L/min) | 18.34–15.46                                 |
| ambient temperature (K) | 298                                         |
| ambient pressure (atm) | 1                                           |

Table 4. Elementary Reaction of N$_2$O (GRI 3.0 Base)

| reaction                        | $A$ (cm$^3$/gmol)/s | $b$ | $E_a$ (kJ/gmol) |
|---------------------------------|---------------------|-----|-----------------|
| N$_2$O(+M) $<=>$ N$_2$ + O(+M)  | $7.9 \times 10^{10}$| 0   | 56 020          |
| N$_2$O + O $<=>$ N$_2$ + O$_2$  | $1.4 \times 10^{12}$| 0   | 10 810          |
| N$_2$O + O $<=>$ 2NO            | $2.9 \times 10^{11}$| 0   | 23 150          |
| NO$_2$ + O $<=>$ NO + O$_2$     | $3.9 \times 10^{12}$| 0   | −240            |
| NO + O + M $<=>$ NO$_2$ + M     | $1.06 \times 10^{30}$| −1.41| 0               |
| N + NO $<=>$ N$_2$ + O          | $2.7 \times 10^{13}$| 0   | 335             |
| N + O$_2$ $<=>$ NO + O          | $9.0 \times 10^9$   | 1   | 6500            |
| 2O + M $<=>$ O$_2$ + M          | $1.20 \times 10^{17}$| −1.00| 0               |
Equation 11 is the modified Arrhenius equation, where $k$ is the rate constant. It can be used as an objective index indicating the characteristics of the chemical reaction rate. The rate of a chemical reaction can be varied using catalysts, which change the activation energy and the reaction route. The rate constant and activation energy are closely related. The rate constant of a reaction depends on the reaction temperature. The reaction rate increases with an increase in temperature due to the increase in the rate constant. In eq 11, A is a frequency or pre-exponential factor, b is a temperature proportional constant, $E_a$ is the activation energy, R is the gas constant, and T is the absolute temperature.

**AUTHOR INFORMATION**

**Corresponding Author**
Jung Goo Hong — School of Mechanical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea; Phone: 82-53-950-6570; Email: jghong70@knu.ac.kr; Fax: 82-53-950-6550

**Authors**
- Jae Geun Yun — School of Mechanical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea
- Han Min Lee — School of Mechanical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea
- Gwang Yeol Baik — School of Mechanical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea
- Ji Yeop Kim — School of Mechanical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea
- Sang Ji Lee — School of Mechanical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea
- Min Kyu Jeon — Department of Environmental Machinery, Korea Institute of Machinery & Materials, Daejeon 34103, Republic of Korea
- Sang In Keel — Department of Environmental Machinery, Korea Institute of Machinery & Materials, Daejeon 34103, Republic of Korea

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c03365

**Author Contributions**
H.M.L., G.Y.B., J.Y.K., S.J.L., M.K.J., and S.I.K. contributed to conceptualization, methodology, software, validation, and data curation; J.G.Y. contributed to writing—original draft preparation; S.I.K. and J.G.H. contributed to writing—review and editing; and J.G.H. contributed to supervision. All authors have read and agreed to the published version of the manuscript.

**Funding**
National Research Council of Science & Technology (NST) grant by the Korean government (MSIP) (No. CRC-15-07-KIER).

**Notes**
The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**
This research was supported by the Technology Development Program to Solve Climate Changes through the National Research Council of Science & Technology (NST) grant by the Korean government (MSIP) (No. CRC-15-07-KIER).

**REFERENCES**

(1) Chang, K. S. Status and Trends of Emission Reduction Technologies and CD Projects of Greenhouse Gas Nitrous Oxide. J. Korean Ind. Eng. Chem. 2008, 19, 17–26.
(2) Choi, S. H.; Ko, J. C. Investigation of N₂O Emission Characteristics and Emission Factors of Solid Fuel Incineration Facilities. J. Korean Soc. Environ. Eng. 2019, 41, 82–88.
(3) Yoon, I. J. In Key Issues and Prospects of the Paris Agreement, Law Research Institute Summer Joint Conference, 2017, pp 113–144.
(4) Jeon, S. G. N₂O Reduction Technology and Catalyst Research and Development Trend. Ind. Chem. Outlook 2016, 19, 33–44.
(5) Cooper, C. D.; Alley, F. C. Air Pollution Control: a Design Approach; Waveland Press, 1994, pp 488–497.
(6) Gullet, B. K.; Paul, W. G.; Lin, M. L.; James, M. C. NO Removal with Combined Selective Catalytic Reduction and Selective Non Catalytic Reduction: Pilot-Scale Test Results. J. Air Waste Manage. Assoc. 1994, 44, 1188–1194.
(7) Jang, J. H. Removal of NOₓ in SNCR Process Using Urea and Additives, Master’s Thesis; School of Environmental Engineering, The University of Seoul, 2003.
(8) Ostberg, M.; Kim, D. J.; Johnsson, J. E. Influence of Mixing on the SNCR process. Chem. Eng. Sci. 1997, 52, 2511–2525.
(9) Oxley, J. C.; Smith, J. L.; Rogers, E.; Yu, M. Ammonium nitrate: Thermal Stability and Explosivity Modifiers. Thermochim. Acta 2002, 384, 23–45.
(10) Smith, R. A.; Mizio, L. J.; Hunt, T. Integrated Dry NOₓ/SO₂ Emissions Control System: Low-NOₓ Combustion System SNCR Test Report, Public service company of Colorado, DOE: DE-FC22-91CPR00550, 1997.
(11) Zeldovich, Y. B.; Barenblatt, G. I.; Librovich, V. B.; Makhviladze, G. M. The Mathematical Theory of Combustion and Explosion; Plenum Press, 1985; p 597.
(12) Jung, M. S. A Study on the Reduction of N₂O generation at SNCR Process Using Urea and Additives, Master’s Thesis; School of Environmental Engineering, The University of Seoul, 2011.
(13) Svoboda, K.; Baxter, D.; Martinez, J. Nitrous Oxide Emissions from Waste Incineration. Chem. Pap. 2006, 60, 78–90.
(14) Amand, L.; Andersson, S. In Emissions of Nitrous Oxide from Fluidized Bed Boilers, International Conference on Fluidized Bed Combustion; 1989; pp 49–56.
(15) Kilpinen, P.; Mikko, H. Homogeneous N₂O Chemistry at Fluidized Bed Combustion Conditions: A Kinetic Modeling Study. Combust. Flame 1991, 85, 94–104.
(16) Kim, J. M. A Study on the Reduction Mechanism of NO and N₂O in Urea-SNCR Process, Master’s Thesis; School of Environmental Engineering, The University of Seoul: Seoul, 2012.
(17) Rahman, Z. U.; Wang, X.; Zhang, J.; Jakob, B.; Millan, V.; Tan, H. Kinetic Study and Optimization on SNCR Process in Pressurized oxy-Combustion. J. Energy Inst. 2021, 94, 263–271.
(18) Liu, S. L.; Fan, W. D.; Shen, P. H.; Wu, X. F.; Chen, J.; Guo, H. The Effect of Iodine Additive and Char on the Heterogeneous Decomposition of N₂O and the Generation of NO under High Temperature. Fuel 2019, 256, No. 115949.
(19) Lee, H. M.; Yun, J. G.; Hong, J. G. A Study of Nitrous Oxide Thermal Decomposition and Reaction in High Temperature Inert Gas. J. ILASS-Korea 2020, 25, 132–138.
(20) Lee, S. J.; Yun, J. G.; Lee, H. M.; Kim, J. Y.; Yun, J. H.; Hong, J. G. Dependence of N₂O/NO Decomposition and Formation on Temperature and Residence Time in Thermal Reactor. Energies 2021, 14, No. 11533.
(21) CHMEKIN-PRO, Reaction Design Inc, San Diego, CA 92121, USA, https://www.ansys.com/.
(22) Smith, G. P.; Golden, D. M.; Frenklach, M.; Moriarty, N. W.; Eiteneer, B.; Goldenberg, M.; Bowman, C. T.; Hanson, R. K.; Song, S.; Gardiner, W. C., Jr.; Lissianski, V.; Qin, Z. http://www.me.berkeley.edu/GRI_Mech/.