Numerical Modeling of Intramolecular Transformations of ortho, meta-Substituted Aromatic Nitroso Oxides

L Enikeeva¹, I Gubaydullin¹² and S Khursan³

¹Ufa State Petroleum Technological University, Kosmonavtov st. 1, Ufa, Russia, 450062
²Institute of Petrochemistry and Catalysis, Russian Academy of Sciences, pr. Oktyabrya 141, Ufa, Russia, 450075
³Ufa Institute of Chemistry, Russian Academy of Sciences, pr. Oktyabrya 71, Ufa, Russia, 450054

e-mail: leniza.enikeeva@gmail.com

Abstract. This work is focused on study of ortho, meta-substituted aromatic nitroso oxides. Nitroso oxides have unique properties due to the cis-trans isomerism phenomenon and one-and-a-half N-O bond order in the nitroso oxide fragment. This paper considers the decay reaction of aromatic nitroso oxides. Considering the complexity of aromatic nitroso oxides, conformational transformations development of a new comprehensive approach using experimental and theoretical tools alongside with mathematical methods and informational technologies is particularly relevant. The main objective of the paper is to develop an algorithm for numerical modeling of aromatic ortho, meta-substituted nitroso oxides decay process. We suggested mathematical models for decay reactions of 2,4-dimethoxyphenyl nitroso oxide and 3-trifluoromethyl-4-methoxyphenyl nitroso oxide. The kinetic modeling allowed us not only to get an agreement between quantum-chemical and experimental data, but also to estimate previously unknown rate constants including the constants for the recombination stages.

1. Introduction
Nitroso oxides, labile peroxide species, are intermediates in reactions proceeding with participation of triplet nitrenes in the presence of oxygen. These labile particles have unique properties due to the cis-trans isomerism phenomenon and one-and-a-half N-O bond order in the nitroso oxide fragment. The chemistry of nitroso oxides is discussed in reviews [1 – 5]. The presence of a substituent at one of the ortho-positions of aromatic nitroso oxide leads to doubling the number of isomeric forms of the species. Thus, there are 4 isomeric forms of nitroso oxide: trans/anti-isomer, trans/cyn-isomer, cis/syn-isomer, and cis/anti-isomer (fig. 1) [6]. The isomer forms of nitroso oxides differ from one another by reactivity in the decay reaction. Let’s consider the decay reaction of aromatic nitroso oxides (see fig. 2).

After flash photolysis of azides in the presence of oxygen in acetonitrile, four isomeric forms of the corresponding nitroso oxides were generated. They are consumed with different rates and led to various products. The isomers of nitroso oxides undergo mutual conformational transformations.
Therefore, the measured rate constant of the isomer decay is effective, i.e. it describes a combination of reversible conformational transitions and irreversible transformations into the reaction products.

Figure 1. Conformers of ortho-substituted phenyl nitroso oxides.

Considering the complexity of aromatic nitroso oxides conformational transformations, development of a new comprehensive approach using experimental and theoretical tools alongside with mathematical methods and information technologies is particularly relevant. The main objective of this paper is to develop an algorithm for numerical modeling of the aromatic ortho, meta-substituted nitroso oxides decay process.

2. Mathematical model

2.1. Mathematical model of transformations of the 2,4-dimethoxyphenyl nitroso oxide conformers (2a)

Figure 3 shows a mechanism of intramolecular transformations of 2,4-dimethoxyphenyl nitroso oxide isomers. The only reaction product is compound 5 (6,7a-dimethoxy-7aH-1,2,3-benzodioxazole). The mathematical model of this reaction is described by a system of 5 ordinary differential equations (ODE) with nine kinetic constants (4 pairs of conformational transformations plus the irreversible consumption of 2a-3) (see fig. 2):

\[
\begin{align*}
\frac{dx_1}{dt} &= -w_1 + w_2 + w_3 - w_5, \\
                   &= w_1 + k_{23}x_2 \\
\frac{dx_2}{dt} &= -w_2 + w_3 - w_3 + w_5 - w_4, \\
                   &= w_2 + k_{34}x_3 \\
\frac{dx_3}{dt} &= -w_3 + w_4 - w_4 + w_6, \\
                   &= w_3 + k_{45}x_5 \\
\frac{dx_4}{dt} &= -w_4 + w_5 - w_3 + w_6, \\
                   &= w_4 + k_{56}x_6 \\
\frac{dx_5}{dt} &= w_5, \\
                   &= w_5 + k_{23}x_2 \\
\end{align*}
\]

where \( x_1 \) is concentration of substance 2a-2, \( x_2 = 2a-3, x_3 = 2a-4, x_4 = 2a-1, x_5 = 5 \). The total initial concentration of 2a was \( 10^{-5} \) M, and the initial distribution of the isomers 2a-1–2a-4 (0.30:0.18:0.34:0.17, respectively) was estimated from the experimental values of their initial optical densities:

\[
\begin{align*}
x_0^1 &= 0.3 \cdot 10^{-3} \ M, \\
x_0^2 &= 0.17 \cdot 10^{-3} \ M, \\
x_0^3 &= 0.34 \cdot 10^{-3} \ M, \\
x_0^4 &= 0.18 \cdot 10^{-3} \ M, \\
x_0^5 &= 0 \ M, \\
\sum_{i=1}^{5} x_i^0 &= 10^{-3} \ M.
\end{align*}
\]
2.2. Mathematical model of transformations of the 2,4-dimethoxyphenyl nitroso oxide conformers (2c)

The reaction products of intramolecular transformations of 3-trifluoromethyl-4-methoxyphenyl nitroso oxide isomers are chemical substances 13 and 14. As the initial conditions for the ODE system solution, the equimolar ratio of the isomers was used. The total initial concentration of 2c was $10^{-5}$ M.

$$
\begin{align*}
\frac{dx_1}{dt} &= -w_j + w_2 + w_5 - w_6, \\
\frac{dx_2}{dt} &= -w_2 + w_3 - w_j + w_4 - w_5, \\
\frac{dx_3}{dt} &= -w_4 + w_5 - w_6 + w_6, \\
\frac{dx_4}{dt} &= -w_6 + w_7 - w_8 + w_8, \\
\frac{dx_5}{dt} &= w_8, \\
\frac{dx_6}{dt} &= w_9,
\end{align*}
$$

Figure 2. Mechanism of the nitroso oxide 2a conformers transformations.

Figure 3. Mechanism of the nitroso oxide 2c conformers transformations.
3. Methods of Calculation

3.1. A direct problem of chemical kinetics
In this paper, the Gibbs energies of all isomers and transition states were calculated during the kinetic modeling of chemical reactions, using the Eyring equation:

\[ k = \kappa \frac{k_B T}{h} \exp \left( \frac{-\Delta G}{RT} \right), \]

where \( \kappa \) – the Wigner tunneling correction factor, \( k_B \) – the Boltzmann constant, \( J/K \), \( T \) – temperature, \( K \), \( h \) – Planck’s constant, \( J \cdot s \), \( \Delta G \) – the change in Gibbs free energy, \( J \), \( R \) – universal gas constant, \( J/(mol \cdot K) \).

The algorithm of solving the direct problem is arranged as follows: using the Gibbs energies of all nitroso oxide isomers and transition states, the changes in Gibbs energies \( \Delta G \) were calculated. Then \( \Delta G \) were substituted into Equation (4) and the rate constants of the nitroso oxides \( 2a, c \) decay reaction were calculated. Having substituted the known rate constants \( k_{ij} \) into the system of ordinary differential equations, the dependence of the concentrations of all the substances involved in the reaction on time was obtained. As the initial approximation, the Gibbs energy obtained by the quantum chemical method were used [7]. The numerical solution of the system of the differential equations was based on the one-iterative Rosenbrock’s method of 3\(^{rd}\) order accuracy.

3.2. Inverse problem of chemical kinetics
While the modeling of the nitroso oxide decay process, the experimental observation of the concentration of nitroso oxides was carried out by decreasing their optical density. For example, in Figure 4, kinetic data on the consumption of the \( cis \) and \( trans \) isomers of a certain nitroso oxide, as well as the formation of the product, are given.

![Figure 4. Experimental kinetic curves – optical density as a function of time.](image_url)

The relationship between the optical density and the concentration of the component is estimated using the following equation:

\[ \varepsilon L = \text{constant} \times x \]

where \( L \) – thickness of the absorbing layer, cm, \( \varepsilon \) – extinction coefficient, \( l/(mol \cdot cm) \), \( x \) – concentration of the component, mol/l. As follows from this equation, the optical density is a linear function of concentration. However, the extinction coefficients of the nitroso oxides \( 2a \) and \( 2c \)
isomers are unknown. Note that all observed particles die strictly according to the kinetic law of the first-order reaction (see Fig. 5). Therefore, the kinetics of the nitroso oxide consumption can be characterized not by a kinetic curve, but by a rate constant of the first order.

![Figure 5. Experimental kinetic curves – optical density as a function of time.](image)

The solution of the ODE system was performed using the one-stage third-order Rosenbrock method and the Matlab R2014a computing environment. The genetic algorithm was chosen as optimization method [8-11]. To solve the direct problem of the conformational transformations process, effective constants were calculated alongside with the yields of reaction products. The obtained results were compared with the experimental data, via minimizing the differences between experimental and calculated values:

\[
\frac{\sum_{i} \left( k_{\text{eff}} - k_{\text{calc}} \right)^2}{\sum_{i} \left( k_{\text{calc}} \right)^2}
\]

where \( k_{\text{eff}} \) and \( k_{\text{calc}} \) – experimental and calculated effective rate constants for the consumption of nitroso oxides isomers, \( i \) – number of constants.

### 4. Results

It was shown that the calculated effective constants agree with the ones obtained experimentally within the allowed tolerance at the room temperature (see Table 1). The rate constants of the elementary stages of the nitroso oxide decay were defined. Constants of conformational stages differed from those at the stages of product formation by no more than two orders of magnitude.

| Isomer    | Calculation | Experiment |
|-----------|-------------|------------|
| 2a-1      | 1.59        | 1.63       |
| 2a-2      | 3.1 \times 10^3 | 3.1 \times 10^3 |
| 2a-3      | 0.14        | 0.14       |
| 2a-4      | 0.76        | 0.77       |
| 2c-1+2c-2 | 0.23        | 0.23       |
| 2c-3      | 9.81        | 9.80       |
| 2c-4      | 0.05        | 0.04       |

Kinetic curves for the consumption of nitroso oxide 2a isomers at the room temperature are presented in Fig. 6. Similar kinetic curves were drawn for the isomers of nitrosooxide 2c. Thus, kinetic models of the reactions of the decay of isomers of nitrosooxides 2a-c at the room temperature have been constructed.

The performance of the model was estimated according to the coefficient of determination \( R^2 \) defined as:

\[
R^2 = 1 - \frac{\sum_{i} \left( k_{\text{calc}} - k_{\text{eff}} \right)^2}{\sum_{i} \left( k_{\text{calc}} \right)^2}
\]
where $x_m$ is the averaged experimental value. The closer $R^2$ to 1 (or 100 %), the better the quality of the model.

![Figure 6. Kinetic curves for the consumption of nitroso oxide 2a isomers at the room temperature.](image)

Note that all presented plots showed the sections of the curves after the inflection point. The analysis of initial plots demonstrated that cis/anti-isomers 2a-4 and 2c-4 are accumulated in the beginning of the reaction, then reach maxima points and finally the consumption of components started (Fig. 7). This agrees with experimental observations. Thus, the developed set of programs for modeling the process made it possible to demonstrate and confirm this observation.

![Figure 7. Kinetic curve of the consumption of cis/anti-isomer 2a-4 nitroso oxide at the room temperature.](image)

Having studied the process at the room temperature its temperature dependence was investigated. To investigate this dependence, it was necessary to modify the program for modeling the process at the room temperature; in the latter program stage constants were calculated using the Eyring’s equation. This equation includes parameter G, which is a function of temperature. Equation was split into two parts – first contains the enthalpy factor, and the second contains entropy:

$$
\begin{align*}
\Delta H &= \text{enthalpy factor} \\
\Delta S &= \text{entropy}
\end{align*}
$$

The algorithm includes the following steps:

- Find enthalpies $H$ at the room temperature.
Using $G$ and $H$ at room temperature as the initial approximation, calculate the optimal values of $G$ and $H$ for several temperatures.

Solving the direct problem for a number of temperatures, determine the effective rate constants for the consumption of all isomers.

Using the Arrhenius equation, calculate $E$ and $k_0$.

Since the activation energies of the consumption of all isomers are positive, the temperature increase accelerates the consumption of the components; is confirmed by the plot at the figures presented below (fig. 8, fig. 9).

**Figure 8.** Experimental and calculated curves for the sum of substances $2a-1 + 2a-2$ concentrations at different temperatures.

**Table 2.** Kinetic parameters of the consumption of isomers $2a$, calculated for the temperature range 283 – 303 K.

|          | $E$, kJ/mol | log $k_0$, 1/sec |
|----------|-------------|------------------|
|          | experiment  | calculation       | experiment | calculation |
| trans/syn| 44 ± 2      | 43               | 8.1 ± 0.3  | 8.0         |
| cis/syn  | 30 ± 1      | 29               | 8.8 ± 0.2  | 8.7         |
| cis/anti | 7.8 ± 0.7   | 7.3              | 0.5 ± 0.1  | 0.4         |
| trans/anti| 49 ± 0.1    | 49               | 8.5 ± 0.3  | 8.5         |

**Figure 9.** Experimental and calculated curves for the concentrations of the sum of substances $2c-1 + 2c-2$ at different temperatures.

**Table 3.** Kinetic parameters for the consumption of isomers $2c$, calculated for the temperature range 298 – 345 K.

|          | $E$, kJ/mol | log $k_0$, 1/sec |
|----------|-------------|------------------|
|          | experiment  | calculation       | experiment | calculation |
| trans    | 69.2 ± 0.9  | 69.7             | 11.5 ± 0.1 | 11.6        |
| cis/syn  | 61.8 ± 0.3  | 63.2             | 11.9 ± 0.1 | 12.1        |
| cis/anti | 0           | -0.03            | -1.36 ± 0.1| -1.36       |
5. Conclusion
Mathematical models for decay reactions of 2,4-dimethoxyphenyl nitroso oxide (2a) and 3-trifluoromethyl-4-methoxyphenyl nitroso oxide (2c) are developed. An algorithm for calculating the effective constants of nitroso oxide isomers consumption, based on quantum chemical data, is developed alongside with an algorithm for searching for optimal values of the formation enthalpies and free Gibbs energies. The latter were inferred from the experimental kinetic curves of the optical density decrease and the yields of the reaction products. The kinetic modeling of the decay of 2a, c is conducted, together with the analysis of the reaction products and quantum-chemical modeling. This clarified the underlying physics of the entire process of aromatic nitroso oxides decay. The results prove that conformational transitions in aromatic nitroso oxides significantly affect the reactivity and chemical transformations of substituted ArNOO. Moreover, kinetic modeling allows us not only to support previously obtained quantum-chemical and experimental data, but also to estimate previously unknown rate constants. A set of programs using the parallel computing technology for modeling the process is developed.

6. References
[1] Chainikova E M, Khursan S L and Safiullin R L 2014 *The Chemistry of Peroxides* 3 357-420
[2] Gritsan N P and Pritchina E A 1992 The mechanism of photolysis of aromatic azides *Russian Chemical Reviews* 61(5) 500
[3] Ishiguro K and Sawaki Y 2000 Structure and Reactivity of Amphoteric Oxygen Species *Bulletin of the Chemical Society of Japan* 73(3) 535-552
[4] Sawwan N and Greer A 2007 Rather exotic types of cyclic peroxides: Heteroatom dioxiranes *Chemical Reviews* 107(7) 3247-3285
[5] Slayden S W, Greer A and Liebman J F 2009 Peroxynitrogen: A Study of Nitrogen Oxygen Heterocycles with N-O and O-O or N-O-O Bonding *John Wiley Sons, Ltd*
[6] Yusupova A R, Khursan S L and Safiullin R L 2016 Conformational Transformations in Aromatic Nitroso Oxides *The Journal of Physical Chemistry A* 120(28) 5693-5705
[7] Chainikova E M, Yusupova A R, Khursan S L, Teregulova A N, Lobov A N, Abdullin M F, Enikeeva L V, Gubaydullin I M and Safiullin R L 2017 Interplay of Conformational and Chemical Transformations of Ortho-Substituted Aromatic Nitroso Oxides: Experimental and Theoretical Study *The Journal of Organic Chemistry* 82(15) 7750-7763
[8] Gubaydullin I, Koledina K and Sayfullina L 2014 Mathematical Modeling of Induction Period of the Olefins Hydroalumination Reaction by Diisobutylaluminiumchloride Catalyzed with Cp2ZrCl2 *Engineering Journal* 18(1) 13-24
[9] Akhmadullina L F, Enikeeva L V and Gubaydullin I M 2017 Numerical methods for reaction kinetics parameters: identification of low-temperature propane conversion in the presence of methane *Procedia Engineering* 201 612-616
[10] Uskov S I, Enikeeva L V, Potemkin D I, Belyaev V D, Snytnikov P V, Gubaidullin I M, Kirillov V A and Sobyavin V A 2017 Kinetics of Low-Temperature Steam Reforming of Propane in a Methane Excess on a Ni-Based Catalyst *Catalysis in Industry* 9(2) 104-109
[11] Gubaydullin I, Enikeeva L and Naik L R 2016 Software module of Mathematical Chemistry web-laboratory for studying the kinetics of oxidation of 4-tert-butyl-phenol by aqueous solution of H2O2 in the presence of titanosilicates *Engineering Journal* 20(5) 263-270