Simkine 2 – Versatile Software for the Computation of Kinetic Profiles of Intricate Chemical Reaction Mechanisms

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ABSTRACT

Simkine 2 is a user-friendly software package developed with the Delphi 5 programming language, for the computation of complex reaction profiles based on a proposed kinetic scheme for the chemical system. The programme applies the semi-implicit extrapolation method (SIEM), which utilizes the implicit midpoint rule and extrapolation. Pre-processor code was designed to translate a user-specified system of chemical rate equations into a system of differential equations. To optimize the estimated rate coefficients manually, Simkine 2 provides a window simultaneously to plot the experimental and corresponding simulated curves in a single run. The software is applied to an intricate 17-step mechanism of the reaction between safranine-O and acidic bromate, which exhibits non-linear kinetics. The four simultaneously plotted computed curves with their experimental profiles are presented as an illustration. A help file is provided.

KEYWORDS

Chemical kinetics, computation, simulations, reaction mechanisms, safranine-O and acidic bromate reaction.

1. Introduction

Modelling and simulations have given great insight into understanding the intricate phenomena, such as bistability, periodicity, spatial temporal behaviour and chaos in both open and closed chemical and biological systems. The validation of proposed mechanisms based on the simulations has become an essential norm in assessing complex chemical systems.[1,2] The simulation models are developed to study the behaviour of the systems over time, based on a set of assumptions that are expressed mathematically, logically and symbolically.[3,4] Kinetic simulation is the imitation of the experimental behaviour with respect to time and involves the investigation and determination of the concentrations of the various reactant, product and intermediate species with respect to time and requires the proposed mechanism for a reaction, the rate constants for each reaction step and the initial concentrations of the starting species. We have recently reported a user-friendly programme, Simkine, and the theory and principles governing the development of that software.[5]

Many of the free or commercial packages, such as NAG (Numerical Algorithms Group), ISML Inc. and Numerical Recipes, provide subroutines that may be incorporated in developing software.[6] Programming languages such as Mathematica and Matlab also provide subroutines usable in developing appropriate software for simulations.

Because of copyright restrictions and the high price associated with some commercial software, free software with technically sound routines and mathematically compatible chemical reactions, which can be duly custom-built, is in great demand. The described program is designed to recognize and rectify the user's errors.

2. Theory

A pre-processor code for a sequence of chemical reactions is described, which translates the user-specified system of chemical rate equations into a system of differential equations.[6,7] Symbolically, these differential equations can be represented as

$$\frac{dx_i(t)}{dt} = f_i(x_1(t),\dots,x_{NSP}(t),k_1(t),\dots,k_{NRATE}(t)) + s_i(t) \qquad (1)$$

where $x_i(t)$ represents the ith time varying chemical species concentration, t is the time variable, NSP is the number of chemical species, $k_j(t)$ represents the time-dependent rate coefficients, $NRATE$ is the number of rate processes, $s_i(t)$ represents a time-varying source, t_0 is the initial value of the time variable and x_i^0 is the initial value of the ith chemical species concentration. Using vector notation, we can represent (Eqn. 1) as a canonical first order initial value problem

$$\frac{dx(t)}{dt} = f(x,t) \qquad (2)$$

The numerical solution of Eqn. (2) is accomplished by using the semi-implicit midpoint rule and extrapolation as follows:

(i) The semi-implicit midpoint rule is used to approximate $x(t + H)$ whenever $x(t)$ is given, using m steps of size $h = H/m$. The result is denoted $x(t + H,h)$.

(ii) Polynomial extrapolation is applied to approximate $x(t + H,h)$ by means of the data obtained from several values of h.

For practical implementation, let $\Delta_n \equiv x_{n+1} - x_n$ and let I denote the identity matrix in the following numerical scheme:

(i) With $h = H/m$, calculate

$$\Delta_0 = \left(I - h\frac{\partial f}{\partial x}\right)^{-1}\left(hf(x_0,t_0) + h^2\frac{\partial f}{\partial t}\right)$$

$$x_1 = x_0 + \Delta_0$$

(ii) For $k = 1,\dots,m-1$, set

$$\Delta_k = \Delta_{k-1} + 2\left(I - h\frac{\partial f}{\partial x}\right)^{-1}(hf(x_k,t_k) - \Delta_{k-1})$$

$$x_{k+1} = x_k + \Delta_k$$

(iii) Compute

$$\Delta_m = \left(I - h\frac{\partial f}{\partial x}\right)^{-1}(hf(x_m,t_m) - \Delta_{m-1})$$

$$\bar{x}_m = x_m + \Delta_m$$

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To handle stiff problems, where computational efficiency is not crucial, the approach commonly used is the semi-implicit Runge-Kutta (RK) method, which is used by Kaps and Rentrop in their program.[4] The Predictor-Corrector methods, which are Gear's backward differentiation methods and the generalizations of the Bulirsch-Stoer methods are also called semi-implicit extrapolation methods (SIEM).[6] These are the most commonly used methods for solving stiff problems in chemical systems. The SIEM methods have gained popularity in the recent past due to their increasing stability with increasing step size, and efficiency/speed with smaller error tolerance. The proposed Simkine 2 program was developed using SIEM, which uses the modified midpoint rule.[6]

The advantages of the Simkine software[5] over other existing software are (i) it comes as an executable file that is ready to be run, therefore the user has no need for contact with the source code, (ii) the user has to supply only the mechanism as a text file using any editor that supports text format, (iii) all data of the species available in the mechanism will be saved as a text file, which can be analysed using any spreadsheet that supports text format, (iv) the number of elementary steps and the number of species in the mechanism have a limit of 40, (v) no programming experience is needed to use the program, (vi) the software will generate the ordinary differential equations and the Jacobian matrix, and (vii) the user need not be concerned about the fitting equation to model the data. The objective of this communication is to provide an improved, versatile and tested version of the program to the chemistry community, now labelled Simkine 2, to compute any intricate chemical mechanism with ease.

3. Discussion

The limitations experienced by us and the other user groups of the Simkine software necessitated these significant improvements to make it much more user-friendly and robust. The problems envisaged in the use of the earlier software are (i) the operating system, (ii) the monotony in the use of the software and (iii) the greater demand for a need to plot experimental and computed data simultaneously.

3.1. The Improvement of the Operating System

The Simkine version of this software was developed using Turbo Pascal for Windows 1.5 (TPW1.5), which was meant to develop software for Windows 3.1 and Windows 95.[8] With the advent of newer versions of Windows, the software developed using TPW1.5 became outdated, as it did not meet the requirements of the newer Windows versions. Thus, Simkine delays the processing time of other software programs running concurrently. This is contrary to the objectives of the Windows technology. That necessitated the development of software compatible with the new operating systems. The Simkine software is now enhanced as Simkine 2, using Delphi Professional 5, which meets the requirements of the new operating systems and operates at high speed.[9]

3.2. The Routine Nature of the Earlier Software

The subroutine STIBS by Press *et al.*, used in Simkine to solve the resulting ordinary differential equations (ODEs), is usual and typecast.[6] When it comes to rigid problems involving numerous reactions and species, it takes longer to calculate the concentrations for all species that are present in the mechanism. As a result, the program may hang up and cause the process to terminate. In Simkine 2, instead of STIBS, the subroutine TLSoda is employed for solving the ODEs generated.[9] The subroutine TLSoda is also based on the functionality of STIBS, when considering the principles involved, except that it uses a backward differentiation method to solve stiff problems. Instead of a MS Word file, an easy to read online help file written using HelpScribble[10] is provided as a separate file to assist Simkine 2 users. Furthermore, the necessity of Simkine to store the data on the selected drive after each run is avoided, as this may compromise the drive, and may end up causing abnormal termination. In Simkine 2, the generated data are available, but will be stored only by preference.

3.3. The Need to Develop Software to Plot Experimental and Computed Data Simultaneously

Most of the available software plots the generated and experimental data separately, and few have the option to plot both for comparison at a later stage. The majority of the software packages allow the plots to be made only after finishing the computation of the data. Overcoming these limitations, the Simkine 2 program plots the experimental curves of all the selected species as the data are generated. While simulating the kinetic profiles, the user needs to view how close the experimental and generated curves match each other. In order to compare the two curves, Simkine 2 makes provision to plot the generated and experimental data on the same set of axes simultaneously. This allows the manual approximation of various estimated rate coefficients or changes in the reaction mechanism with least effort and greatest efficiency, to achieve maximum agreement between the experimental and computed profiles. In addition, Simkine 2 also provides an opportunity to plot simultaneously numerous experimental curves (generated with specific species as variables) and their respective simulated curves in one attempt, for the chosen optimized parameters. The same single run also provides the concentration–time data for all species (reactants, products and intermediates) in the mechanism for the chosen conditions of each of the experimental curves. To demonstrate the utility and versatility of the Simkine 2 program, the kinetic data and proposed mechanism for the reaction of safranine-O, a phenoxazine dye, with acidic bromate from our earlier published experimental work is used.[11]

Academic interest in the safranine-O/acidic bromate reaction arises from its autocatalytic behaviour, with very slow depletion of the organic substrate initially, followed by a very fast reaction later. During reaction, bromide ion, a reaction intermediate, plays a dual role, both as the autocatalyst and as an inhibitor exhibiting complex oxidation kinetics. In the Belousov-Zhabotinskii-type chemical systems, bromide ion, which switches between high and low concentration conditions acts as a control intermediate.[1,2] The change from high to low bromide concentration occurs through the reaction of bromide with $HBrO_2$ and BrO_3^-. Regeneration of Br^- depends upon the nature of the organic intermediates and their reaction rates with various oxybromo and bromo species in the system. The crucial equations representing the chemistry of the safranine-O/acidic bromate reaction are represented as follows:[11]

E1. $2\,H^+ + Br^- + BrO_3^- \rightleftharpoons HOBr + HBrO_2$
E2. $H^+ + Br^- + HBrO_2 \rightleftharpoons 2\,HOBr$
E3. $H^+ + Br^- + HOBr \rightleftharpoons Br_2 + H_2O$
E4. $HBrO_2 + H^+ \rightleftharpoons H_2BrO_2^+$
E5. $HBrO_2 + H_2BrO_2^+ \rightarrow 2H^+ + HOBr + BrO_3^-$
E6. $H^+ + BrO_3^- + HBrO_2 \rightleftharpoons Br_2O_4 + H_2O$
E7. $Br_2O_4 \rightleftharpoons 2\,BrO_2^{\bullet}$

In the safranine-O/acidic bromate system, in the absence of initially added bromide, the induction time reflects the time

Table 1 Safranine-O reaction with bromate in acidic solutions (rate coefficients used for simulations).

No.	Forward		Reverse	Rate constants, k_f and k_r
E1.	$2H^+ + Br^- + BrO_3^-$	$\rightleftharpoons$	$HOBr + HBrO_2$	$2.5\ dm^9\ mol^{-3}\ s^{-1}$; $3.2\ dm^3\ mol^{-1}\ s^{-1}$
E2.	$H^+ + Br^- + HBrO_2$	$\rightleftharpoons$	$2\ HOBr$	$2.5 \times 10^6\ dm^6\ mol^{-2}\ s^{-1}$; $2.5 \times 10^{-5}\ dm^3\ mol^{-1}\ s^{-1}$
E3.	$H^+ + Br^- + HOBr$	$\rightleftharpoons$	$Br_2 + H_2O$	$8.0 \times 10^9\ dm^6\ mol^{-2}\ s^{-1}$; $8.0 \times 10^1\ s^{-1}$
E4.	$HBrO_2 + H^+$	$\rightleftharpoons$	$H_2BrO_2^+$	$2.0 \times 10^6\ dm^3\ mol^{-1}\ s^{-1}$; $1.0 \times 10^8\ s^{-1}$
E5.	$HBrO_2 + H_2BrO_2^+$	$\rightarrow$	$2H^+ + HOBr + BrO_3^-$	$1.7 \times 10^5\ dm^3\ mol^{-1}\ s^{-1}$
E6.	$H^+ + BrO_3^- + HBrO_2$	$\rightleftharpoons$	$Br_2O_4 + H_2O$	$4.8 \times 10^1\ dm^6\ mol^{-2}\ s^{-1}$; $3.2 \times 10^3\ s^{-1}$
E7.	Br_2O_4	$\rightleftharpoons$	$2\ BrO_2^\bullet$	$7.5 \times 10^4\ s^{-1}$; $1.4 \times 10^9\ dm^3\ mol^{-1}\ s^{-1}$.
E8.	$SA^+ + BrO_3^- + 2H^+$	$\rightarrow$	$SB^+ + HBrO_2 + H^+$	$5.74 \times 10^{-4}\ dm^9\ mol^{-3}\ s^{-1}$
E9.	$SA^+ + BrO_2^\bullet$	$\rightarrow$	$SA^{+\bullet} + HBrO_2$	$6.83 \times 10^5\ dm^3\ mol^{-1}\ s^{-1}$
E10.	$SA^{+\bullet} + BrO_2^\bullet + H_2O$	$\rightarrow$	$SB^+ + HBrO_2$	$3.92 \times 10^5\ dm^3\ mol^{-1}\ s^{-1}$
E11.	$SA^+ + HOBr$	$\rightarrow$	$SB^+ + H^+ + Br^-$	$8.43 \times 10^2\ dm^3\ mol^{-1}\ s^{-1}$
E12.	$SA^+ + Br_2 + H_2O$	$\rightarrow$	$SB^+ + 2H^+ + 2Br^-$	$6.82 \times 10^3\ dm^3\ mol^{-1}\ s^{-1}$
E13.	$SA^+ + HBrO_2$	$\rightarrow$	$SB^+ + HOBr$	$1.91 \times 10^2\ dm^3\ mol^{-1}\ s^{-1}$
E14.	$SB^+ + HOBr + H_2O$	$\rightarrow$	$SP + HNO + 2H^+ + Br^-$	$6.95 \times 10^3\ dm^3\ mol^{-1}\ s^{-1}$
E15.	$SB^+ + Br_2 + H_2O$	$\rightarrow$	$SP + HNO + 3H^+ + 2\ Br^-$	$3.2 \times 10^4\ dm^3\ mol^{-1}\ s^{-1}$
E16.	$SB^+ + HBrO_2$	$\rightarrow$	$SP + HNO + HOBr + H^+$	$1.55 \times 10^3\ dm^3\ mol^{-1}\ s^{-1}$
E17.	$HNO + HNO$	$\rightarrow$	$N_2O + H_2O$	$4.5 \times 10^9\ dm^3\ mol^{-1}\ s^{-1}$

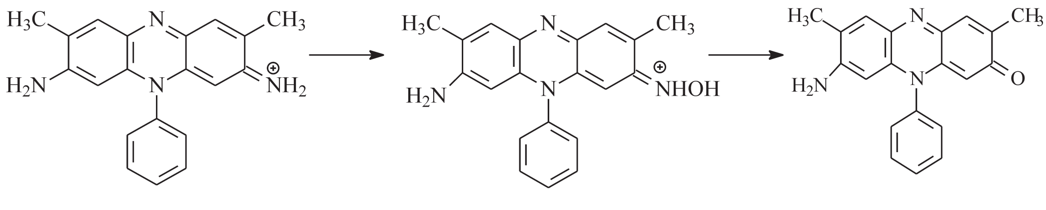
required for the accumulation of $HBrO_2$ and the removal of trace inhibiting species, including bromide, present as impurities with bromate. The rate-limiting step in such a system is direct reaction between safranine-O (SA^+) and BrO_3^- in presence of acid, which is followed by the formation of $BrO_2^\bullet$ radical.

E8. $SA^+ + BrO_3^- + 2H^+ \rightarrow SB^+ + HBrO_2 + H^+$
E9. $SA^+ + BrO_2^\bullet \rightarrow SA^{+\bullet} + HBrO_2$
E10. $SA^{+\bullet} + BrO_2^\bullet + H_2O \rightarrow SB^+ + HBrO_2$
E11. $SA^+ + HOBr \rightarrow SB^+ {}^+ H^+ + Br^-$
E12. $SA^+ + Br_2 + H_2O \rightarrow SB^+ + 2H^+ + 2Br^-$
E13. $SA^+ + HBrO_2 \rightarrow SB^+ + HOBr$
E14. $SB^+ + HOBr + H_2O? \rightarrow SP + HNO + 2H^+ + Br^-$
E15. $SB^+ + Br_2 + H_2O \rightarrow SP + HNO + 3H^+ {}^+ 2\ Br^-$
E16. $SB^+ + HBrO_2 \rightarrow SP + HNO + HOBr + H^+$
E17. $HNO + HNO \rightarrow N_2O + H_2O$

The reactions of organic intermediates with BrO_3^-, $HBrO_2$ and HOBr are retarded by high bromide concentration through its competitive reaction with the oxybromo species. High concentration of bromide inhibits the autocatalysis step (E6), via E2, depleting the bromous acid concentration. Thus, the accumulation of $HBrO_2$ is delayed, prolonging the induction period for the rapid depletion of SA^+. The fast depletion step is the result of the rapid reaction of safranine-O with Br_2 and HOBr. The increased concentration of $HBrO_2$ enhances its disproportion rate. At high $HBrO_2$ concentration, with the bromide concentration at a critical level, bromide acts as an autocatalyst (E2), resulting in an increase in concentration of HOBr. Both Br_2 and HOBr could react rapidly with SA^+ and other organic species leading to the fast depletion of the organic substrate. Relative levels of HOBr and Br_2 are controlled by the concentrations of H^+ and Br^- ions (E4). In addition, $HBrO_2$ also reacts directly with the organic intermediates.

The oxidation of safranine-O (SA^+) results in the formation of a transient intermediate, probably an oxime (SB^+), followed by further oxidation.[11–13] During the oxidation involving bromine and hypobromous acid, the formation of brominated aromatics as transient intermediates in oxidation reactions involving bromine are well known (Scheme 1).[14]

Table 1 summarizes the 17 steps involved in the proposed mechanistic scheme, together with the rate coefficients for each elementary step of the reaction. The rate constants listed are from the literature experiments and estimated values for the different elementary steps.[11] Figure 1 shows the four experimental curves depicting the effect of variation of initial bromate concentration on the kinetic profiles of the safranine-O (SA^+) depletion, for the reaction between SA^+ and acidic bromate, under conditions of excess concentrations of bromate and acid, and the four respective simulated curves for identical conditions using the Runge-Kutta method[4] and the Simkine 2 software. The curves simulated by both approaches were identical, except for the procedure for putting together the requisite information. For the Runge-Kutta method,[4] the simulated curves from the data generated in four separate computations have to be appended together with the respective experimental curves to construct the diagram, while Simkine 2 generated all the experimental and simulated curves in one exercise. Further, the latter method facilitates the manual approximation of various estimated rate parameters and mechanistic steps with ease and minimal effort. Perusal of Fig. 1 shows



SA^+ SB^+ SP

Scheme 1

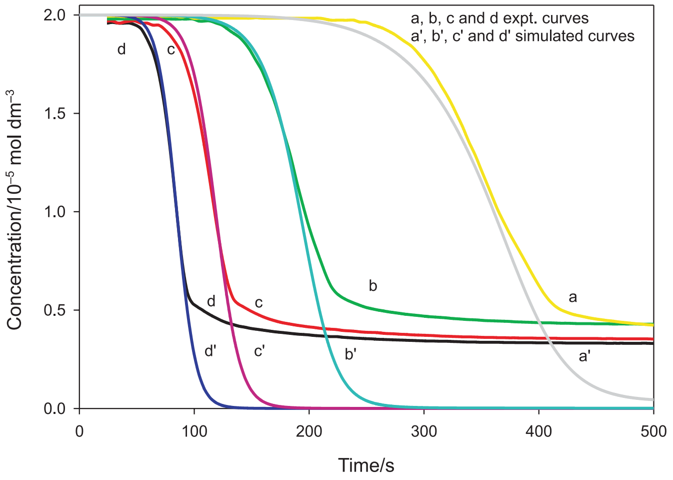


Figure 1 Experimental and simulated curves using Simkine 2: safranine-O and acidic bromate reaction: $[SA^+] = 2.0 \times 10^{-5}$ mol dm^{-3}, $[H^+] = 0.20$ mol dm^{-3} and $[BrO_3^-]$ = (a) 0.0075, (b) 0.01, (c) 0.015 and (d) 0.02 mol dm^{-3}: a′, b′, c′ and d′ are the respective simulated curves.

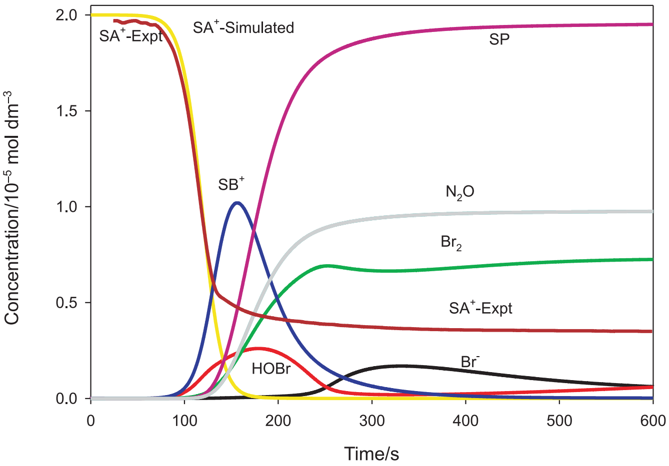


Figure 2 Computed profiles of selected reactants, intermediates and products of the reaction using Simkine 2: $[SA^+] = 2.0 \times 10^{-5}$ mol dm^{-3}, $[H^+] = 0.2$ mol dm^{-3} and $[BrO_3^-] = 0.02$ mol dm^{-3}.

the plots of the four experimental curves and the corresponding simultaneously computed curves using Simkine 2 (as a text file to be read by any spreadsheet), which are exactly similar to the curves generated using the Runge-Kutta method. Furthermore, Simkine 2 also generates the concentrations of the all the species (reactants, intermediates and products) involved in the mechanistic scheme, allowing the evaluation of the aptness of the estimated rate coefficients. Figure 2 shows the simulated kinetic profiles of the selected reaction intermediates and products generated using Simkine 2 for one reaction run, together with the corresponding experimental and simulated curves for depletion of safranine-O for a chosen set of experimental conditions.

4. Conclusions

The Simkine 2 program, developed with the Delphi 5 programming language, has a robust subroutine for stiff integrated systems and has a provision simultaneously to plot numerous experimental and simulated curves in a single computation. Further, it provides a versatile and user-friendly ambience to the chemist for computation of any intricate multi-step kinetic mechanism with ease.

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Supporting Information

To test the adaptability and scope of the Simkine 2 software, a Zip file containing the Simkine 2 exec (Simkine.doc), the help file (Simkine.hlp), the experimental data file (SAexpts.txt) and the mechanism file (Mechanism.txt) for the safranine-O/acidic bromate reaction is available. The .exe file is added as a .doc file for security reasons in internet transmissions. Thus, the Simkine.doc file needs to be converted into a Simkine.exe file before use.

References

1 R.M. Noyes, *Acc. Chem. Res.*, 1990, **23**, 258–269.
2 S.B. Jonnalagadda, *Pure Appl. Chem.*, 1998, **70**, 645–650.
3 J. Banks, J.S. Carson II and B.L. Nelson, *Discrete-Event System Simulation*, 2nd edn., Prentice Hall International Inc., Englewood Cliffs, NJ, USA,1996, pp. 16–32.
4 P. Kaps and P. Rentrop, *Numer. Math.*, 1979, **33**, 55–63.
5 S.B. Jonnalagadda, N. Paramasur and M.N. Shezi, *Comput. Biol. Chem.*, 2003, **27**, 147–152.
6 W.H. Press, B.P. Flannery, S.A Teukolsky and W.T.Vetterling, *Numerical Recipes*: *The Art of Scientific Computing* (*Fortran Version*), 2nd edn., Cambridge University Press, New York, NY, USA,1992, pp. 19–42.
7 B. Long, *The Borland Pascal Problem Solver,* Addison-Wesley, Wokingham, England, 1994, pp. 311–325.
8 B. Rector, *Developing WINDOWS-3. Applications with Microsoft SDK,* Carmel, IN, USA, 1991, pp. 46–58.
9 H.M. Sauro, *TLSoda – Stiff Differential Equation Solver,* Future Skill Software, Livermore, CA, USA, December 1996. URL: http://www.fssc.demon.co.uk/Delphi/delphi.html.
10 J. Goyvaerts, *HelpScribble Demo 7.2.0,* Just Great Software (JGsoft), Nonthaburi, Thailand, June 2003. URL: http://www.helpscribble.com/demo.html.
11 S.B. Jonnalagadda, M. Shezi and N.R. Gollapalli, *Intern. J. Chem. Kinet.*, 2002, **34**, 542–549.
12 J.C. Sullivan and R.C. Thomson, *Inorg. Chem.*, 1979, **18**, 2375–2383.
13 S.B. Jonnalagadda, Intern. *J. Chem. Kinet.*, 1984, **16**, 1287–1294.
14 I. Szalai and E. Koros, J. *Phys. Chem.*, 1998, **102**, 6892–6901.