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Kinetic and Safety Characterization of the Nitration Process of Methyl Benzoate in Mixed Acid

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ABSTRACT: The nitration of methyl benzoate is studied from a chemical and a kinetic point of view. The reaction network through which the system could evolve following the loss of thermal control or the uncorrect feed of the reagents is completely characterized. The data collected during the present investigation indicate that runaway phenomena can occur during the nitration of the substrate due to the development of side reactions. Isothermal experiments are thus carried out to estimate the unknown kinetic parameters through the adoption of a mathematical model able to predict the system behaviour upon variation of process parameters. The dependence of the acidity function H on the operating conditions is assessed. The proposed model and the estimated parameters are validated through the use of the results collected in a set of experimental runs performed at significantly different operating conditions from those adopted to identify them.

1. INTRODUCTION

Methyl m-nitrobenzoate is a useful starting material for the preparation of dyes and crop agent.[1] This important intermediate is currently obtained through the nitration of methyl benzoate by means of mixed acid[2](an aqueous mixture of nitric and sulfuric acids). Although this process is well-known and it is currently used in school laboratories as a simple example of aromatic electrophilic substitution,[3,4] there are no indications in the literature about the kinetic parameters of interest or about the network of reactions that can be involved in it. Generally speaking, it is well-known that, being nitrations exothermic reactions, runaway phenomena can occur during these processes as the result of polynitration and/or side reactions which take place when thermal control of the process is lost.[5] With respect to this aspect it is useful to remember that nitrations are along with polymerizations among the most dangerous reactions at industrial level also for the inherent thermal instability of the products.[6,7] On the basis of these considerations, the characterization of the reaction network through which the system of interest could evolve is attempted from chemical and kinetic point of view.[8] Investigations are carried out by considering, as process deviations, the loss of thermal control and an uncorrected feed of the reagents. On the basis of the structure of the substrate adopted in the present study, the occurrence of both polynitration and hydrolysis reactions are expected following these process deviations. In particular, a relevant influence on the system reactivity of the protonating power of the medium (acidity function) may be foreseen. Different relationships[9−11] for the acidity function dependence on the temperature and the composition of the mixed acid were found in the literature. Therefore, the present investigations seeks at assessing the most reliable relationship to be used for the estimation of the acidity function value related to an adopted mixed acid. The ultimate goal of present work is thus the collection of all the information necessary to develop a complete kinetic model able to simulate the behaviour of the studied system for different possible initial conditions.

2. EXPERIMENTAL SECTION

For all isothermal experiments a jacketed glass magnetically stirred[a] (volume: 3.0×10^{-2} L) reactor has been used. The temperature has been kept at desired value by using a Julabo F32 refrigerated/heating circulator (cooling fluid: water). All the runs have been carried out in batch mode. For each run 1.0×10^{-2}–1.5×10^{-2} L of mixed acid with specific composition have been prepared adding, dropwise, a desired amount of water and, successively, of nitric acid to sulfuric acid under cooling, between 283 and 293 K. The temperature has been then increased up to the desired value and an amount of organic substrate has been instantaneously added to the solution. In particular for each run, the concentration of the involved species as a function of reaction time has been recorded by submitting chemically quenched samples, with a dilution in methanol (1.0×10^{-4} L of each sample withdrawn from the reactor at varying reaction time were rapidly diluted in 10^{-2} L), collected during the experiments, to HPLC analysis using a Hewlett-Packard model 1100 II, equipped with an UV−vis detector and a Phenomenex Synergi 4 μ polar RP/80A column. During the preliminary work to tune all the experimental procedures, it has been checked that no changes in the concentration of the species analyzed were observed repeating the HPLC analysis at different times on the same solution kept at room temperature. The following operating conditions have been adopted: the mobile phase has been formed by 70% of a buffer solution (vol %: CH_3OH 5%, H_3PO_4 0.4%, H_2O 94.6%) and 30% of acetonitrile, the signals have been acquired at 210, 220, 230, 240 nm, the column temperature has been kept at 298 K and the flow rate set at 1×10^{-3} L × min^{-1}. For all the experiments analytical grade

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reagents have been used (H_2SO_4 98% was obtained from Fluka and the other reagents from Sigma Aldrich).

3. RESULTS AND DISCUSSION

It is well-known that the loss of thermal control is one of the most frequent and dangerous process deviations in chemical industry[12,13] which may result into a runaway event and, in some cases, into a thermal explosion with severe damages to people and plants. In particular, in the case of nitration processes, it is clear that an unwanted increase of the temperature can give rise to polynitrations and/or other side reactions.[14] On the basis of these considerations, during a safety assessment for a chemical process, the complete reaction network through which the system could evolve needs to be identified.[15] For these reasons preliminary experiments of nitration of methyl benzoate with mixed acid at ambient or near ambient temperature have been performed. The data obtained indicated that the main product is methyl m-nitrobenzoate, with a minor occurrence of methyl p-nitrobenzoate. Since it is well-known that an increase of the reaction temperature favors polynitration reactions of aromatics with the formation of di- and trinitroderivatives,[16] whereas an uncorrected feed of the amount of the water can give rise to hydrolysis reactions of the species involved in the process with the formation of the corresponding organic acids,[17] a complex reaction network can be expected to originate from the successive reactions of the above-reported species. To better understand the dangerousness of the system of interest some simple calculations can be done. On the basis of the results of preliminary experiments it can be stated that the mononitration reactions start approximately at room temperature, the ester hydrolysis at temperatures around 320 K, whereas the dinitrations become relevant near 340 K. Assuming a heat of reaction equal to 1060 J/g for the nitration of methyl benzoate (by means of a group contributing calculations[18]), considering an amount of mixed acid equal to two times the mass of the substrate (a common choice in industrial applications) and a mean specific heat equal to 2 J/g K, in the case of a total loss of the cooling power (adiabatic conditions), it is possible to calculate an adiabatic temperature rise due to the complete mononitration of the substrate as:

$$\Delta T_{ad} = \frac{\Delta H_{nit}}{3 \cdot cp_M} = 117K \qquad (1)$$

Following the results of this calculation and considering a process temperature for mononitration equal to 290 K, it can be stated that-under adiabatic conditions- the side reactions, polynitrations and hydrolysis of the products, can surely start (Figure 1). Moreover, considering a heat of reaction equal to 803 J/g for the nitration of the mononitroderivatives and keeping constant the ratio between the total mass and the reagent mass (in order to make the calculation easier), it is clear that the temperature rise in the reactor could become dangerously relevant. In fact, for the complete nitration of the mononitrobenzoate an additional temperature rise of 134 K is obtained. The final temperature[b] due to the unwanted side reactions will be thus between the following two calculated values: 470 and 604 K (Figure 2). Moreover, it is foreseeable that in this temperature range the thermal decomposition of products starts. On the basis of the considerations done, a set of experiments has been thus planned and performed to identify the reactions really occurring when the temperature increases.

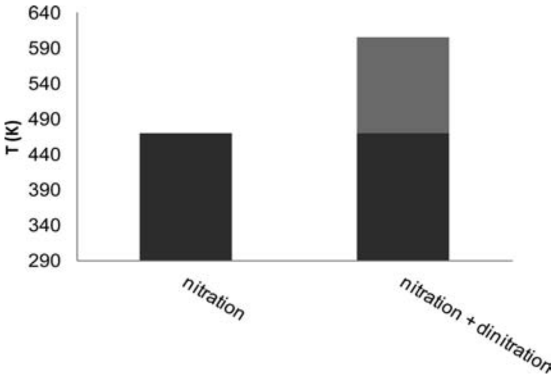


Figure 1. Comparison between the starting temperatures and generated heats for the considered reaction: mononitration and dinitration.

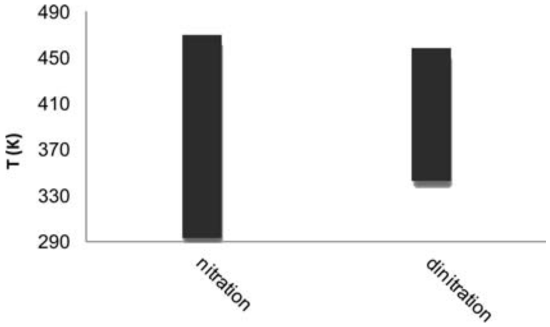


Figure 2. Possible temperature rises due to the combination of the considered reactions.

The nitration of methyl benzoate (MB) has been investigated, under isothermal conditions, at different temperatures and nitrating mixture compositions. The operating conditions adopted are reported in table 1.

Table 1. Operating conditions adopted in the experiments performed on methyl benzoate

T (K)	[MB] (mol/L)	[HNO3] (mol/L)	[H2SO4] (mol/L)	[H2O] (mol/L)
283	0.224	4.52	9.14	16.59
288	0.224	4.52	9.14	16.59
293	0.224	4.52	9.14	16.59
293	0.270	5.06	8.72	16.05

The data obtained in a run performed at 288 K are reported in figure 3; it is clear that the main product was methyl m-nitrobenzoate (3NMB), with a significant occurrence up to around a yield of 20% of methyl p-nitrobenzoate (4NMB). Similar results have been obtained in the other runs performed.

Successively, the reactivity of methyl m-nitrobenzoate has been investigated (initial system composition, units mol/L: $C_{3NMB} = 0.27$, $C_{HNO3} = 6$, $C_{H2SO4} = 12.2$, $C_{H2O} = 5.5$; T=343 K).

The gathered information (Figure 4) pointed out that the compound was converted into methyl 3,5-dinitrobenzoate (3,5DNMB) through the successive nitration and into 3-nitrobenzoic acid (3NBA) through the hydrolysis. Both species can be converted into 3,5-dinitrobenzoic acid (3,5DNBA): 3,5DNMB through a hydrolysis reaction whereas 3NBA through a nitration step (scheme 1). It is important to stress

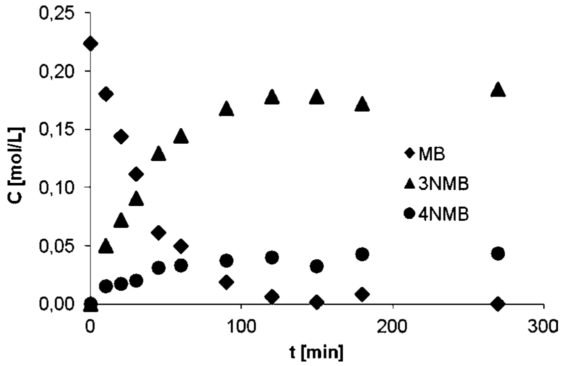


Figure 3. Methyl benzoate nitration at 288 K. Initial system composition: C_{MB} = 0.224 mol/L, C_{HNO3} = 4.52 mol/L, C_{H2SO4} = 9.14 mol/L, C_{H2O} = 16.59 mol/L.

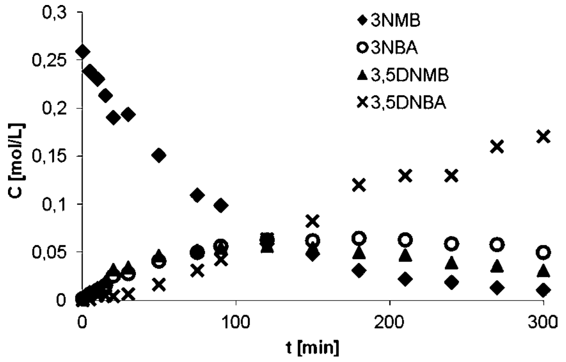
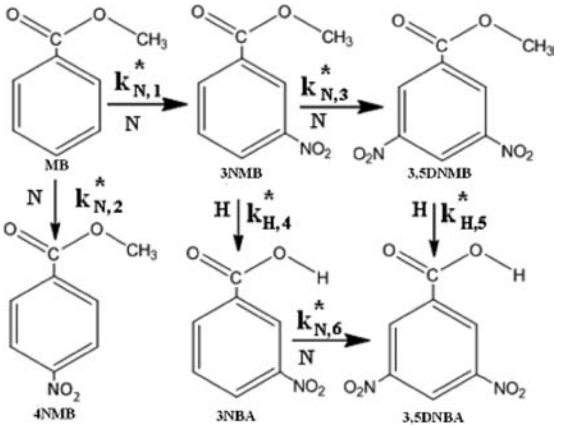


Figure 4. Methyl m-nitrobenzoate nitration and hydrolysis at 343 K. Initial system composition: C_{3NMB} = 0.27 mol/L, C_{HNO3} = 6 mol/L, C_{H2SO4} = 12.2 mol/L, C_{H2O} = 5.5 mol/L.

Scheme 1. Reaction network identified during the investigations



that the selectivity between the two different reactions (nitration and hydrolysis) depends upon the composition of mixed acid, an increase of the water concentration favoring the hydrolysis.

3.1. KINETIC ASSESSMENT

The results previously collected and discussed clearly indicate that a loss of the thermal control or an uncorrected feed of the reagents during the nitration process of methyl benzoate can give rise to a complex reaction network which could result into a thermal explosion. It is well-known that a thermokinetic characterization of the investigated system is among the most important requirements for the adoption of safe operating conditions devoted to prevent the occurrence of unwanted events. Therefore, with the aim of estimating the kinetic parameters of the reactions involved when the nitration of methyl benzoate is carried out in the presence of a loss of the thermal control or with an uncorrected feed of the reagents, a new set of isothermal experiments has been performed. Four subsystems obtained respectively by the reactions involving the species identified in the scheme 1 (3NMB, 3,5DNMB and 3NBA) have been taken into account for further investigations; in particular, in the case of 3NMB, being this specie involved in both the reactions, nitration and hydrolysis, the two different pathways have been thus separately studied. In other words, the four reactive steps, that is, the hydrolysis of 3NMB, the nitration of 3NMB, the hydrolysis of 3,5DNMB and the nitration of 3NBA, have been separately investigated carrying out some experimental runs at different temperatures and different nitrating mixture compositions. In table 2 the operating conditions adopted in the experiments performed on 3NMB have been reported; it is important to stress that an increase of the amount of the water in the nitrating mixture favors the hydrolysis. This last sentence becomes clear by comparing figures 4 and 5[c]; in fact, the results reported in figure 5 are related to a run performed on the system at the same temperature of that whose data are shown in figure 4, 343 K, but with a different mixture composition, in particular with a higher ratio water/substrate with respect to the other (see table 2).

The same procedure has been adopted for the other subsystems identified in the previous step; in other words. the runs have been first performed at fixed initial concentrations of both substrate and nitrating mixed, varying the temperature and successively, at temperature values already tested, the experiments have been repeated with different reactive mixture compositions (data not reported).

On the basis of the results obtained during this investigation a mathematical model aiming at describing the system behaviour under the different operating conditions analyzed has been developed.

In detail, for each species included in the scheme 1, a material balance equation has been written:

$$\frac{dC_i}{dt} = \sum_{p=1}^{n} \pm k^*_{N,p}\cdot C_j\cdot C_{HNO_3} \pm \sum_{l=1}^{h} \pm k^*_{H,l}\cdot C_j\cdot C_{H_2O}^2 \tag{2}$$

The subscript i indicates the i-th species, whereas the subscript j the j-th species participating in the p-th nitration or in the l-th hydrolysis, including the possibility that i is equal to j. The parameter k* represents a gross kinetic constant, which makes possible to use a simple power law to describe the disappearance and formation of involved species. On the basis of the reaction mechanisms, known from the literature for both nitration and hydrolysis, the true kinetic laws are reported below[d]:

$$r_N = k_N\cdot C_{NO_2^+}\cdot C_{ArH} = k_{0N}\cdot \exp\left(\frac{-E_N}{R\cdot T}\right)\cdot C_{NO_2^+}\cdot C_{ArH} \tag{3}$$

$$r_H = k_H\cdot C_{H_2O}\cdot C_{ArH^+} = k_{0H}\cdot \exp\left(\frac{-E_H}{R\cdot T}\right)\cdot C_{H_2O}\cdot C_{ArH^+} \tag{4}$$

were C_{ArH} is the concentration of the organic substrate participating in the nitration and $C_{ArH}{}^+$ is the concentration

Table 2. Operating conditions adopted in the experiments performed on methyl m-nitrobenzoate

T [K]	reaction *N* = nitration H=hydrolysis	[3NMB] (mol/L)	[HNO_3] (mol/L)	[H_2SO_4] (mol/L)	[H_2O] (mol/L)	[H_2O]/[3NMB]
323	N	0.27	6.00	12.20	5.50	20.37
323	N	0.27	6.31	12.73	3.30	12.22
338	N	0.28	6.00	12.20	5.50	19.64
343	N	0.27	6.00	12.20	5.50	20.37
343	N	0.48	6.80	11.70	5.50	11.46
313	H	0.20	4.48	9.05	16.50	82.50
323	H	0.18	4.48	9.05	16.50	91.67
343	H	0.20	4.48	9.05	16.50	82.50
323	H	0.25	5.30	10.63	8.80	35.20

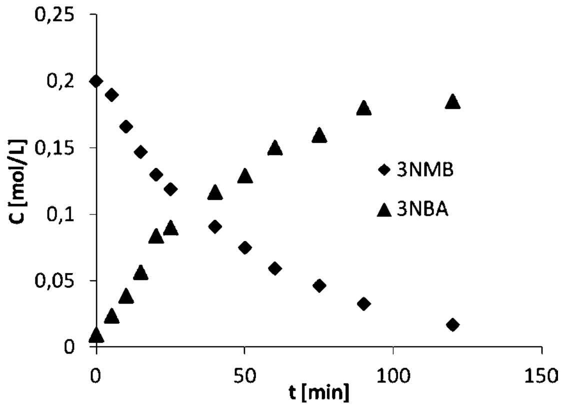


Figure 5. Methyl m-nitrobenzoate hydrolysis at 343 K. Initial system composition: C_{3NMB} = 0.20 mol/L, C_{HNO3} = 4.48 mol/L, C_{H2SO4} = 9.05 mol/L, C_{H2O} = 16.50 mol/L.

of protonated substrate involved in the hydrolysis reaction. $C_{NO2}{}^{+}$ and $C_{ArH}{}^{+}$, in the eqs 3 and 4, can be derived from the equilibria established in the reactive systems:

$$C_{NO_2^+} \cong a_{NO_2^+} = \frac{K_{eq(a)} \cdot a_{HNO_3 \cdot H_2O} \cdot a_{H_2SO_4}}{a^2_{H_2O \cdot HSO_4^-}} = \frac{K_{eq(a)} \cdot a_{HNO_3 \cdot H_2O} \cdot a_{H_2SO_4}}{a^2_{H_2O \cdot HSO_4^-}} \quad (5)$$

$$C_{ArH^+} \cong a_{ArH^+} = \frac{K_{eq(b)} \cdot a_{ArH} \cdot a_{H_2SO_4}}{a_{HSO_4^-}} = \frac{K_{eq(b)} \cdot C_{ArH} \cdot \gamma_{ArH} \cdot \gamma_{H_2SO_4}}{\gamma_{HSO_4^-}} \cdot \frac{C_{H_2SO_4}}{C_{HSO_4^-}} \quad (6)$$

It is possible to assume that small concentrations C_{NO2+} and C_{ArH+} are equal to the corresponding activities. Introducing the acidity function H, defining a gross pre-exponential factor k^f_{0R} and a gross activation energy E^f_R (where R is equal to N for the nitration and H for the hydrolysis) and considering an Arrhenius-like equation for the global gross kinetic constant k_R:

$$H = -\log \frac{a_{H_2SO_4}}{a_{H_2O} \cdot a_{HSO_4^-}} \quad (7)$$

$$k^f_{0R} = k_{0R} \cdot e^{(\Delta S_{(j)}/R)} \quad (8)$$

$$E^f_R = E_R + \Delta H^0_{(j)} \quad (9)$$

$$k^f_R = k^f_{0R} \cdot e^{(-E^f_R/R \cdot T)} \quad (10)$$

where j is referred to the equilibrium (a) for the nitration and to equilibrium (b) for the hydrolysis.

So the eqs 3 and 4 became:

$$r_N = k^f_N \cdot \frac{\gamma_{HNO_3 \cdot H_2O}}{\gamma_{H_2O}} \cdot 10^{-H} \cdot \frac{1}{C_{H_2O}} \cdot C_{HNO_3} \cdot C_{ArH} \quad (11)$$

$$r_H = k^f_H \cdot \gamma_{H_2O} \cdot 10^{-H} \cdot C^2_{H_2O} \cdot C_{ArH} \quad (12)$$

Therefore, the eq 2 can be just obtained assuming:

$$k^*_N = k^f_N \cdot \frac{\gamma_{HNO_3 \cdot H_2O}}{\gamma_{H_2O}} \cdot 10^{-H} \cdot \frac{1}{C_{H_2O}} \quad (13)$$

$$k^*_H = k^f_H \cdot \gamma_{H_2O} \cdot 10^{-H} \quad (14)$$

To solve the obtained differential equations system, the knowledge of the activity coefficients for the ternary system $HNO_3/H_2O/H_2SO_4$[9] is required along with a suitable relationship for H. From a literature survey different and conflicting relationships[9−11] have been found to describe the dependence of H on the temperature and on the composition of the mixed acid. Therefore, in the present investigation, an equation of the following type has been adopted:

$$-H = (a \cdot C_{H_2SO_4} + b \cdot C_{HNO_3}) \cdot \left(z + \frac{g}{T}\right) \quad (15)$$

in which the coefficients a, b, z and g have been considered as unknown parameters to be estimated.

The experimental results obtained during the runs performed on each reactive subsystem identified in the reaction scheme 1 have been simultaneously used in a single optimization procedure to estimate the unknown gross kinetic parameters k^f_{0R} and E^f_R, defined in the eqs 8 and 9, and the coefficients a, b, z and g in the eq 15. The adopted procedure has been based on the minimization of an objective function defined as:

$$\varphi = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{i=1}^{m} (y_{i,j,l} - C_{i,j,l})^2 \quad (16)$$

In which the terms y and C are the calculated and experimental concentration whereas m, n, and h are the number of experimental data recorded in each experiment, the number of the substances and the number of the experiments used in the optimization procedure respectively. Some examples of comparison of calculated (continuous lines) and experimental (symbols) concentration are shown in Figures 6−10[e] for each subsystem identified in the reactive scheme:

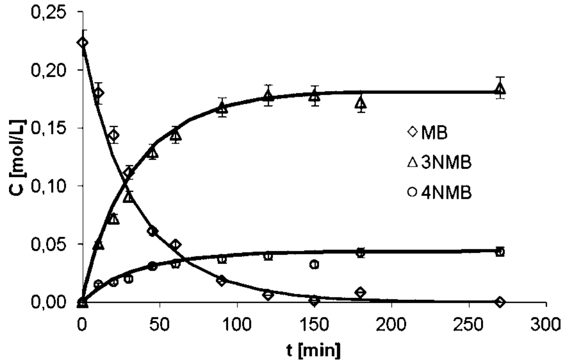


Figure 6. Comparison between experimental (symbols) and calculated (continuous lines) data for methyl benzoate nitration at 288 K. Initial system composition: C_{MB} = 0.224 mol/L, C_{HNO3} = 4.52 mol/L, C_{H2SO4} = 9.14 mol/L, C_{H2O} = 16.59 mol/L.

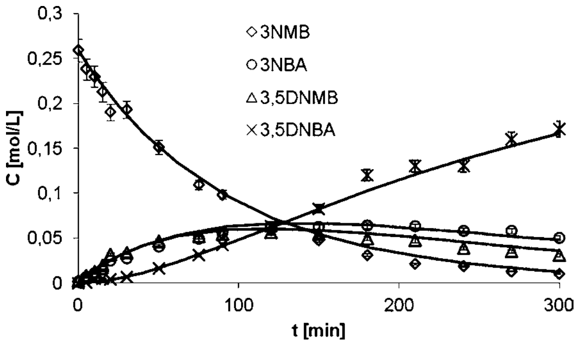


Figure 7. Comparison between experimental (symbols) and calculated (continuous lines) data for methyl m-nitrobenzoate nitration and hydrolysis at 343 K. Initial system composition: C_{3NMB} = 0.27 mol/L, C_{HNO3} = 6 mol/L, C_{H2SO4} = 12.2 mol/L, C_{H2O} = 5.5 mol/L.

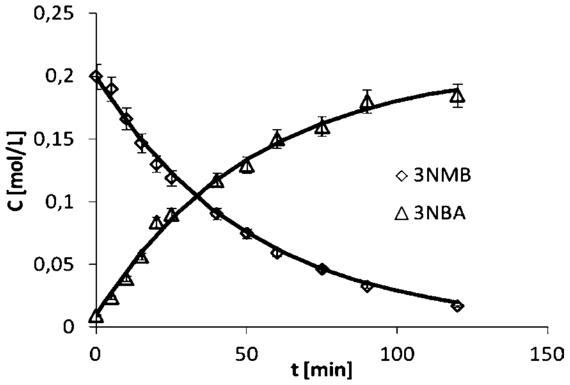


Figure 8. Comparison between experimental (symbols) and calculated (continuous lines) data for methyl m-nitrobenzoate hydrolysis at 343 K. Initial system composition: C_{3NMB} = 0.20 mol/L, C_{HNO3} = 4.48 mol/L, C_{H2SO4} = 9.05 mol/L, C_{H2O} = 16.50 mol/L.

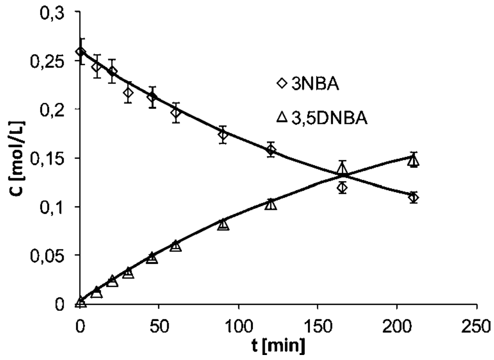


Figure 9. Comparison between experimental (symbols) and calculated (continuous lines) data for 3-nitrobenzoic acid nitration at 343 K. Initial system composition: C_{3NBA} = 0.26 mol/L, C_{HNO3} = 6.02 mol/L, C_{H2SO4} = 12.20 mol/L, C_{H2O} = 5.60 mol/L.

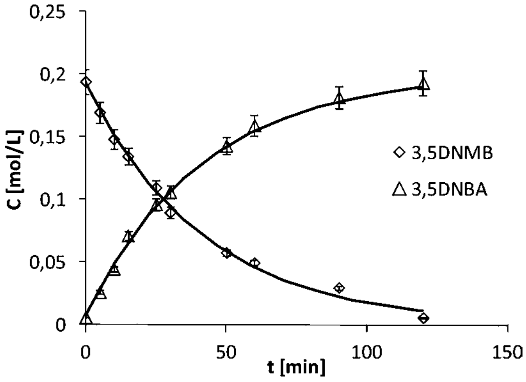


Figure 10. Comparison between experimental (symbols) and calculated (continuous lines) data for methyl 3,5-dinitrobenzoate hydrolysis at 343 K. Initial system composition: $C_{3,5DNMB}$ = 0.19 mol/L, C_{HNO3} = 4.63 mol/L, C_{H2SO4} = 9.50 mol/L, C_{H2O} = 16.70 mol/L.

Table 3. Best estimated values for the unknown kinetic parameters identified in scheme 1

reaction	E^f_R [kJ/mol]	k^f_{0R} [reaction dependent]
1	79.1 ± 4.2	$10^{(9.61\pm0.4)}$
2	68.2 ± 5.0	$10^{(7.06\pm0.3)}$
3	107.2 ± 7.9	$10^{(8.25\pm0.5)}$
4	86.2 ± 6.2	$10^{(5.94\pm0.3)}$
5	92.9 ± 5.4	$10^{(7.24\pm0.4)}$
6	87.9 ± 7.1	$10^{(5.25\pm0.3)}$

The estimated values of the unknown kinetic parameters are reported in table 3, whereas for a, b z and g coefficients the following values have been evaluated: a=0.56 ± 0.028 L mol^{-1}, b=0.52 ± 0.022 L mol^{-1}, z=0.33 ± 0.015 and g=49.0 ± 2.1 K.

To validate the proposed model[f], two additional nitration runs have been performed on 3NMB starting from initial concentrations higher (0.95 mol/L and 1.14 mol/L) than those used in previous experiments (0.18 mol/L÷0.48 mol/L). Also in this condition the system kept at constant temperature during the runs and the proposed model well predicts its behaviour (Figures 11 and 12). Therefore, it can be stated that the model is capable to predict the system behaviour at varying its composition provided that it is perfectly homogeneous; that is, the developed model can be applied for experimental conditions in which no immiscible phases are present, since no equations to account for material transport are included in it.

4. CONCLUSIONS

The behaviour of the system methyl benzoate/mixed acid has been studied when a loss of the thermal control or an uncorrect feed of the reagents happens. In these conditions, the possibility of occurrence of runaway phenomena and thermal explosion has been demonstrated as a result of a process development

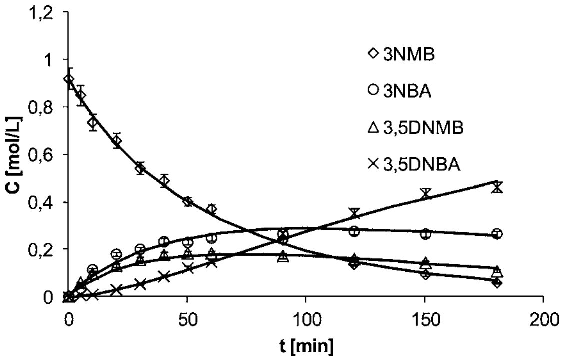


Figure 11. Comparison between experimental (symbols) and calculated (continuous lines) data for methyl m-nitrobenzoate nitration and hydrolysis at 343 K at initial concentrations higher than those used previously. Initial system composition: C_{3NMB} = 0.92 mol/L, C_{HNO3} = 6.75 mol/L, C_{H2SO4} = 11.00 mol/L, C_{H2O} = 5.90 mol/L.

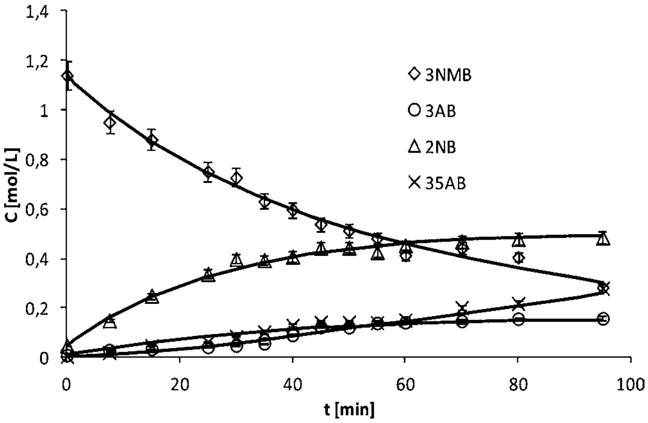


Figure 12. Comparison between experimental (symbols) and calculated (continuous lines) data for methyl m-nitrobenzoate nitration and hydrolysis at 345 K at initial concentrations higher than those used previously. Initial system composition: C_{3NMB} = 1.14 mol/L, C_{HNO3} = 8.50 mol/L, C_{H2SO4} = 9.00 mol/L, C_{H2O} = 4.50 mol/L.

through a complex reaction network. Kinetic assessments have been performed for each reaction of the network allowing the assessment of the dependence of gross kinetic parameters upon temperature and the protonating power of the medium. Satisfactory results have been obtained in a validation procedure of estimated kinetic parameters, which have been used to simulate the data collected during additional nitration experiments, still under isothermal conditions, on more concentrated systems than those used to develop the model.

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Notes

The authors declare no competing financial interest.

■ NOMENCLATURE

ΔT_{ad}	Adiabatic temperature rise K
ΔH_R	Heat of R-th reaction J g^{-1}
c_{pM}	Mean specific heat J $g^{-1}K^{-1}$
C_i	Concentration of i-th species mol L^{-1}
T	Temperature K
R	Universal constant of gas J mol^{-1} K^{-1}
$k^*_{H,i}$	Gross kinetic constant for i-th hydrolysis L^2 mol^{-2} min^{-1}
$k^*_{N,i}$	Gross kinetic constant for i-th nitration L mol^{-1} min^{-1}
k_R	Kinetic constant for R-th reaction L mol^{-1} min^{-1}
r_R	Velocity of R-th reaction mol L^{-1} min^{-1}
k^0_R	Pre-exponential factor for R-th reaction L mol^{-1} min^{-1}
E_R	Activation energy for R-th reaction kJ mol^{-1}
t	Reaction time min
a_i	Activity of i-th species mol L^{-1}
γ_i	Activity coefficient of i-th species dimensionless
H	Acidity function dimensionless
k^f_R	Gross kinetic constant for R-th reaction (L^2 mol^{-2} min^{-1}) or (min^{-1})
E^f_R	Gross activation energy for R-th reaction kJ mol^{-1}
k^f_{0R}	Gross pre-exponential factor for R-th reaction (L^2 mol^{-2} min^{-1}) or (min^{-1})
y_i	Calculated concentration of i-th species mol L^{-1}
$\Delta S_{(j)}$	Entropy change for the j-th equilibrium J K^{-1} mol^{-1}
$\Delta H^0_{(j)}$	Entalpy change for the j-th equilibrium J mol^{-1}

■ ADDITIONAL NOTES

[a] Generally speaking an efficient stirring is really important to carry out a nitration process in which two immiscible phases (organic and aqueous ones) are contacted. In the present work, since the primary interest was that of achieving a basic kinetic characterization of the studied system, we investigated the nitration of methylbenzoate under experimental conditions in which only a single phase was present (in other words, the system was perfectly homogeneous!). In this case, the sole mixing that could be critical was that of the substrate and mixed acid, at the beginning of the run, when the first was poured in the second one. Direct observations done for many runs indicated that with the magnetic mixing we have chosen, after a very short time (20−30 s), an homogeneous single phase was obtained.

[b] Calculations have been done with a conservative approach. Therefore, the final temperatures have been calculated by considering a closed system. Consequently, no water vaporization heat has been considered in the thermal balance.

[c] At high water content and 70 °C the nitration of 3NMB does not occur.

[d] In the eqs 2 and 4 the concentration of water is present with two different orders. Obviously this is not a mistake! In fact, eq 4 is obtained by considering the rate-determining step in the hydrolysis process which is represented by the attack of water on protonated ester molecule (water concentration present at a first order). In the eq 2 the final form is reported which can be obtained by making the appropriate substitutions in eq 4 (water concentration present at second order).

[e] With reference to Figure 6 the reviewer asks about the origin of the parameters used for profile calculation. These parameters have been estimated by means of an optimization procedure which is based on the minimization of the objective function (eq 16) and makes use of all the experimental data collected during the runs at the same time. In other words, the values of the parameters have been estimated as those which make possible to calculate the concentration profiles which show the best fitting with the experimental data.

[f] In the text it has been reported that some validation runs have been performed. These have been done mainly to demonstrate that the estimated values of the parameters may allow to predict

the behaviour of the system also at varying the initial conditions. In particular, two validation runs (Figure 11 and 12) have been carried out at starting concentrations of the substrate significantly higher than those adopted in the other experiments whose results have been used to estimate the values of the unknown parameters. Generally, we can state that the model is capable to predict the system behaviour provided that this is perfectly homogeneous, no matter the starting composition of mixed acid or the concentration of the substrate; that is, the developed model cannot be applied for conditions in which two immiscible phases are present, since no equations to account for material transport are included in it.

■ REFERENCES

(1) Hackenberger, A.; Patsch, M.; Gaeng, M. *Preparation of Methyl m-nitrobenzoate*, U.S. Patent 4,506,089, 1985.

(2) Kamm, O.; Segur, J. B. *Org. Synth.* **1941**, *1*, 372.

(3) Clarke, D. D. Abstracts, 42nd Middle Atlantic Regional Meeting of the American Chemical Society, College Park, MD, United States, May 21–24, 2011.

(4) Hudson, M. J.; Isaacs, N. S.; Wheeler, J. G. *School Science Review.* **1980**, *62* (219), 330–332.

(5) Kozak, G. D.; Raikova, V. M. *Cent. Eur. J. Energetic Mater* **2010**, *7* (1), 21–32.

(6) Maddison, N.; Rogers, R. L. *Chemical Technology Europe* **1994**, *1* (5), 28–31.

(7) Kozak, G. D.; Vasin, A. Ya.; Dyachkova, A. V. New Trends in Research of Energetic Materials, Proceedings of the Seminar, 11th, Pardubice, Czech Republic, Apr. 9–11, 2008, 381-386.

(8) Andreozzi, R.; Canterino, M.; Caprio, V.; Di Somma, I.; Sanchirico, R. *J. Hazard. Mater.* **2006**, *A138*, 452–458.

(9) Zaldivar, J. M.; Barcons, C.; Molga, E.; Snee, T. *J. Chem. Eng. Sci.* **1992**, *47*, 2517–2522.

(10) Cook, M. J.; Dassanayake, N. L.; Johnson, C. D.; Katrizky, A. R.; Toone, T. W. *J. Am. Chem. Soc.* **1975**, *97*, 760.

(11) Kanhere, J. M.; Chandalia, S. B. *Ind. Eng. Chem. Process. Des. Dev.* **1981**, *20*, 407–409.

(12) Casson, V.; Lister, D. G.; Milazzo, M. F.; Maschio, G. *J. Loss Prev. Process Ind.* **2012**, *25* (1), 209–217.

(13) Gustin, J. L. *J. Loss Prev. Process Ind.* **1993**, *6* (5), 275–291.

(14) Andreozzi, R.; Caprio, V.; Di Somma, I.; Sanchirico, R. *J. Hazard. Mater.* **2006**, *A134*, 1–7.

(15) Stoessel, F. *Thermal Safety of Chemical Processes*; Wiley-VCH: New York, 2008.

(16) Raikova, V. M.; Ivanova, O. A.; Shraiber, G. A. New Trends in Research of Energetic Materials, Proceedings of the Seminar, 10th, Pardubice, Czech Republic, Apr. 25–27, 2007, 866-875.

(17) Gunaydin, H.; Houk, K. N. *J. Am. Chem. Soc.* **2008**, *130* (46), 15232–15233.

(18) Medard, L. A. *Accidental explosions* Vol. *1*; Ellis Horwood Limited: Chichester, 1989.