



Continuous nitration of *o*-dichlorobenzene in micropacked-bed reactor: process design and modelling

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Abstract

The matching of the micro-dispersion method and the reaction kinetics is of the utmost importance for the fast and strongly exothermic nitration reaction. Taken as an example to discuss this issue, a synthesis of 3,4-dichloronitrobenzene via the nitration of *o*-dichlorobenzene with mixed acid of nitric acid and sulfuric acid was conducted in continuous-flow reactors in this work. Through combining the adiabatic reaction environment, the use of a micropacked-bed reactor, and introducing partial product circulation, it successfully achieved the matching of the micro-dispersion state and the reaction kinetic characteristics. The good two-phase dispersion state can be maintained throughout the micropacked-bed reactor and the reaction can be completed within 5 s with above 89% selectivity under adiabatic condition. Furthermore, the reaction activation energy was conveniently obtained by processing the temperature distribution data, providing a fundamental to realize a reliable design of the nitration reaction process with high efficiency and inherent safety.

Keywords *o*-dichlorobenzene · 3,4-dichloronitrobenzene · Adiabatic nitration · Continuous-flow · Micropacked-bed reactor

Introduction

Nitroaromatic compounds are an important class of organic intermediates widely used in dyes, pharmaceuticals, explosives, perfumes, pesticides, and other fields [11, 16]. The common nitration system used a mixed acid of nitric acid and sulfuric acid as the nitrating reagent, which participated in the reaction by generating nitroxyl cations NO_2^+ [8, 21]. The synthesis of dye intermediate 3,4-dichloronitrobenzene (**2**) from *o*-dichlorobenzene (**1**) is a typical example of mixed acid nitration, as shown in Scheme 1. The 2,3-dichloronitrobenzene (**3**) is main

by-product due to the orientation effect of the chlorine substituent. In the industry, this nitration reaction was conventionally carried out in a stirred tank reactor, by dripping nitric acid for up to 4 h at low temperature, and then holding the reaction at 60 °C for 2 h [3, 9, 27]. Due to the high viscosity of sulfuric acid and the strongly exothermic reaction of nitration, it is hard for the stirred tank to meet the requirements of the nitration reaction in mass and heat transfer [11, 30]. Due to the lack of effective control of the reaction heat and two-phase contact, this process suffers from low production efficiency, unstable product quality, high energy consumption, and poor reliability of equipment amplification. More importantly, the process of aromatic nitration releases a large amount of heat. If it is not properly controlled, the temperature may be out of control, even causing an explosion. Therefore, it is a challenging and rewarding work to develop an efficient, safe, and controllable nitration reaction process through reaction process intensification strategies.

For those reactions limited by mass/heat transfer of liquid–liquid system, continuous flow and microreactor technology are effective tools for process intensification [19, 28]. The large specific surface area in the microchannel reactor can enable high mass and heat transfer efficiency, thus improving the mixing performance, heat removal performance, and safety performance of the reaction process [7, 14, 17, 31].

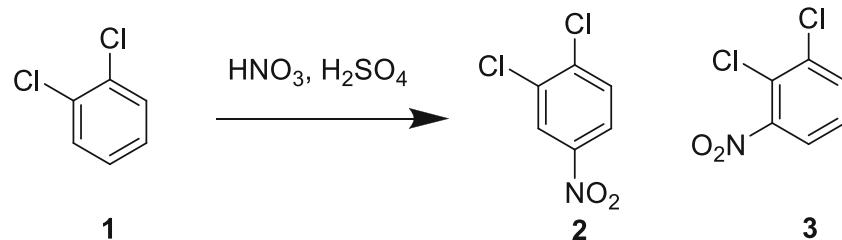
Article Highlights

- Study apparent reaction kinetic of the nitration of *o*-dichlorobenzene under various micro-dispersion methods.
- Proposed strategy combination of the adiabatic and micropacked-bed reactor for process intensification and control.
- Enable rapid determination of activation energy by the measurement of adiabatic temperature rise.

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Scheme 1 Nitration reaction of *o*-dichlorobenzene



Compared with traditional batch reaction, continuous flow can better control the reaction parameters and may help complete the reaction in a shorter time and with better selectivity, which is of great benefit to the nitration reaction with rapid and strong exothermic reaction characteristics [11]. In recent years, the reported substrates of the nitration process under continuous flow control mainly included *o*-nitrotoluene [24], 5-bromo-2-amino-4-methylpyridine [6], 2-ethylhexanol [12], trifluoromethoxybenzene [29, 30], benzaldehyde [19], dimethyl aniline [22], 3-fluorobenzotrifluoride [2], and *o*-toluic [33], among others. Most of these works were carried out under isothermal conditions, which helped to study the kinetics and improve reaction selectivity. But it often requires a lot of cold sources to remove the nitration reaction heat to maintain the constant temperature for the reaction. Due to the strong exothermic and fast reaction characteristics of nitration, even under the microfluidic control, absolute isothermal conditions cannot be well guaranteed upon the two phases are mixed, which will be more difficult in industrial scale-up. In contrast, for adiabatic nitration, it does not need the cold source to control reaction temperature, and the reaction can be accelerated by its reaction heat, corresponding low-energy consumption, and reliable process control [18]. Su et al. [33] conducted dinitration of *o*-toluic acid in an adiabatic continuous-flow system to obtain optimal residence time. The HPLC yields of product 3,5-dinitro-2-methylbenzoic acid between the isothermal (130°C) and adiabatic (room temperature to 173°C) conditions were similar, but the energy consumption of adiabatic reactions was greatly reduced. However, until now, the reports on the adiabatic nitration process in microfluidics were still limited [18, 32, 33]. Most of them only proved that the reaction under adiabatic was feasible, and the optimization of reaction conditions including the residence time was just based on conditional experiments, which was unable to support quantitative process analysis and design towards further application.

Besides, although the micromixer can provide a good dispersion state for the liquid-liquid two phases instantaneously, the dispersed droplets are easy to coalescence quickly in the delay tube due to relatively large differences in density and high viscosity, thereby affecting the subsequent reaction [10, 25]. Therefore, maintaining a good dispersion state until the

reaction process completion is essential to strengthen the reaction. It is necessary to match the micro-dispersion method with the reaction kinetic characteristics, which is also the key to making the reaction process controllable thoroughly. Among various microreactors, micropacked-bed reactor is a competitive tool to intensify the dispersion and mixing of the reaction process due to their excellent multi-phase mixing effect by secondary breakage, easy preparation, and support for catalysts [5, 23, 24, 29, 34]. Micropacked-bed reactors have important applications in gas-liquid and liquid-liquid two-phase reactions controlled by the mass transfer, such as oxidation [1], hydrogenation [20], hydrogenolysis [26], and cross-coupling reaction [15].

Herein, for the liquid-liquid two-phase reaction of nitration of **1** by mixed acid, reaction kinetic characteristics under different micro-dispersion methods were investigated. To achieve the matching of the micro-dispersion state and the reaction kinetic characteristics, we propose a strategy with the combination of the adiabatic nitration, the employ of a micropacked-bed reactor, and the introduction of partial product circulation. Through online monitoring the reaction temperature under adiabatic conditions, the changes in the reaction process can be figured out, especially the impact of some internal components of the reactor. And a method for rapid determination of the reaction activation energy is developed by the interpretation of adiabatic temperature rise. Thus, we hope to realize a reliable design of the nitration reaction process of **1** with high efficiency and inherent safety.

Experimental

Chemicals

Analytical grade *o*-dichlorobenzene (>99%; Aladdin, China), 3,4-dichloronitrobenzene (>97%; Aladdin, China), 2,3-dichloronitrobenzene (>98%; Aladdin, China), and sulfuric acid (H_2SO_4 , >98%; Zhejiang Hanoun Chemical Technology Co., China) were used directly without further purification. Industrial grade fuming nitric acid (>97%) and chlorobenzene (>99%) were obtained from Zhejiang Runtu Co., Ltd. (Zhejiang, China).

Experimental setup

The platforms of continuous nitration are illustrated in Fig. 1. On feed was the mixed acid of sulfuric acid and nitric acid. The other feed was **1** or the mixture of **1** and **2**. Both of them were pumped into the preheating tube (ID, 0.80 mm; OD, 1.60 mm; 316 L) by two constant flux pumps (Beijing Xingda Science and Technology Development Co., Ltd.; flow rate, 0–30.00 mL/min; pressure range, 0–20 MPa), respectively. These two streams mixed in the T-type micromixer (ID, 0.25 mm; SS316L; Valco Instruments Co. Inc.), and then passed through the reaction tubes switched by the switch valve. The reaction tubes had three types: a thin tube (ID, 0.75 mm; OD, 1.60 mm; ETFE), a thick tube (ID, 4 mm; OD, 6 mm; 316 L), and a micropacked-bed reactor (ID, 4 mm; OD, 6 mm; 316 L; filled with glass beads; PTFE mesh (0.150 mm) set at both ends to fix the glass beads). Three kinds of glass beads (ASONE Co.) were used in with the micropacked-bed reactor, of which the size was 0.177–0.250 mm, 0.350–0.500 mm, and 0.500–0.710 mm, respectively. Correspondingly, the void fraction was determined to be 34%, 38%, and 40%, respectively. The packing density was kept at about 1.5–1.6 g/cm³. The length of reaction tubes adjusted according to the required residence time; the reaction tubes were placed vertically, and the fluid flowed from top to bottom. The connecting tube between the micromixer and the reaction tubes was 5 cm in length and 0.75 mm in ID. After a certain residence time, the effluent was collected by a sample bottle with ice water to quench the reaction.

For the isothermal nitration, preheating tubes, the T-type micromixer, and reaction tubes were placed in a water bath (\pm 0.5 °C; ZNCL-GS-CX30; Henan Aibote Technology Development Co. Ltd.), as shown in Fig. 1a. And for the adiabatic nitration, preheating tubes were placed in a water bath; the T-type micromixer, connecting tube, and reaction tubes were wrapped by multiple layers of thermal insulation cotton (including the materials with very low thermal conductivity, such as the glass fiber, the aluminum silicate fiber, the rubber-plastic sponge) to provide a nearly adiabatic

environment, as shown in Fig. 1b. The verification of the adiabatic performance of this equipment was detailed in Supplementary Information. The reaction temperature was monitored and recorded by a multi-channel temperature recorder (\pm 0.1 °C; BCL2016P; Dongguan Bufan Electronic Co. Ltd.). Temperature sensors were evenly spaced along the reaction tube to acquire the temperature of the tube surface.

Analysis method

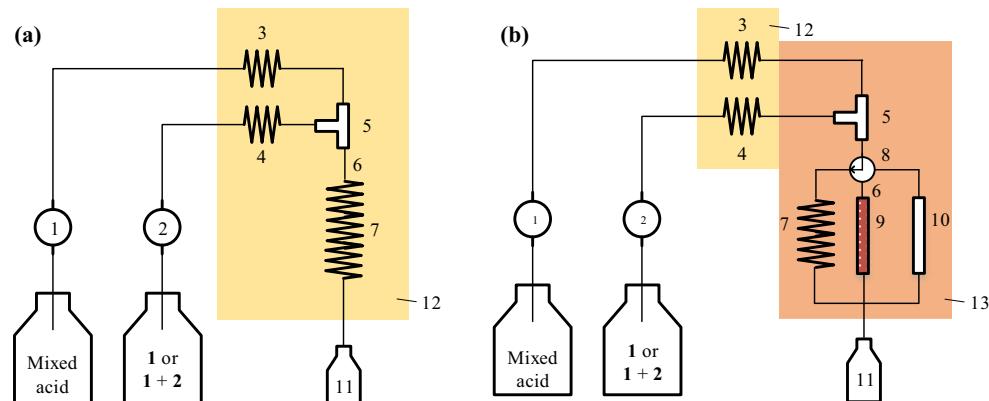
The quenched sample in the sampling bottle is a mixture of dilute acid and organics. Considering that the solubility of **1**, **2** and **3** in water is extremely low, the sample was diluted to neutral, and then the organics were dissolved and extracted by chlorobenzene with approximately 100% recovery of organic materials. The organic mixture with chlorobenzene was taken as the GC sample for analysis. The GC sample (0.5 μ L) was injected in the GC-2014 instrument (Shimadzu) equipped with a DB-FFAP column (length, 30 m; ID, 0.320 mm; film thickness, 0.25 μ m). The oven temperature was maintained at 140 °C for 5 min, then increased to 240 °C by 15 °C/min, and then held for 5 min. The flow rate of the nitrogen as the carrier gas was 1.0 mL/min with a split ratio of 30:1; the injector and FID detector temperatures were set to 280 °C and 300 °C, respectively. The contents of **1**, **2** and **3** were determined by using the area normalization method.

Results and discussion

Reaction kinetics characterization and intensification

To reveal the kinetics characterization of the nitration reaction, the reaction was firstly explored under the isothermal platform as shown in Fig. 1a, which is a simple type of microreactor combining a micromixer and a thin tube providing 160 s of residence time. The effect of reaction temperature was depicted in Fig. 2a. As the reaction temperature rose from 10

Fig. 1 Schematic representation of the experimental set-up: **a** isothermal nitration; **b** adiabatic nitration. 1 and 2: Delivery pumps; 3 and 4: preheating tube; 5: T-type micromixer; 6: connecting tube; 7: thin tube; 8: switch valve; 9: micropacked-bed reactor; 10: thick tube; 11: sample bottle; 12: water bath; 13: adiabatic insulation



to 60 °C, the conversion increased from 57.13% to 99.57%, and the selectivity decreased from 91.34% to 86.60%. Higher reaction temperature corresponded to lower selectivity, although the declination was not remarkable.

The effect of the nitration ratio, the molar ratio of nitric acid to **1**, was examined and the results were shown in Fig. 2b. More nitric acid usage brought a more complete reaction. Nevertheless, the amount of nitric acid had little effect on the selectivity which was maintained at about 89.2%. It implied that the temperature control was effective since the reaction rate was relatively slow.

However, for this liquid-liquid two-phase reaction, the micromixer was only used to provide the initial dispersion, and the phase separation was prone to occur in the empty delay tube, which may seriously reduce the reaction efficiency and controllability. And if the nitration reaction rate is accelerated through keeping microdispersion state, it may be difficult to maintain an ideal isothermal condition. To avoid a reaction process being out of control, we put forward the strategy combining the adiabatic nitration and the employ of a micropacked-bed reactor in the following.

The reaction platform of the adiabatic nitration was illustrated in Fig. 1b. By the multi-point temperature measurement, the temperature distribution along the reaction tubes can be obtained, and Fig. 3 shows the temperature distributions under different feed compositions. Data processing results of adiabatic nitration were listed in Table 1. It can be found directly from the profiles of temperature (Fig. 3) that the addition of products can effectively reduce the reaction temperature rise. In detail, when the raw material was 100% **1**, the temperature rise of the reaction was as high as 200 °C; when the proportion of **1** in the organic feed was 25%, the temperature rise was only about 40 °C. For all the experiments shown in Fig. 3, the poly-nitration by-products and the raw material in the outlet were always at trace amounts from the GC determination. So, the reaction heat may be mainly attributed to mono-nitration reactions, the reaction heat of which

can be calculated from the adiabatic temperature rise [35] (more details can be found in Supplementary Information). As shown in Table 1, when there were more raw materials in the feed and the temperature rise was higher, the calculated reaction heat was relatively high, which may be caused by secondary reactions such as the decomposition of nitric acid. When the mass ratio of raw material to the product was 1:3, the temperature rise was low, and the calculated reaction heat (-139.15 kJ/mol) was similar to that obtained from the standard enthalpy of formation (-142.53 kJ/mol), indicating that the scope of reaction temperature was appropriate and the secondary reaction could be ignored. Under this condition, the conversion could be calculated from the ratio of the actual temperature rise to the maximal temperature rise, and the selectivity was also similar to that of the isothermal temperature reaction. In other words, the introduction of partial product circulation enabled the controllability of the adiabatic nitrification of **1** at the circulation ratio of 3:1 (the recirculation rate to the discharge rate); the utilization of a micropacked-bed reactor can retain the micro-dispersion state and enhance the apparent reaction kinetics significantly.

Furthermore, the data of temperature obtained by different temperature measurement points can convert into the data of conversion and residence time (more details can be found in Supplementary Information). In this way, the reaction kinetics information under adiabatic conditions can be acquired efficiently, bringing conveniences in process investigation and improvement. Herein, we investigated the effects of system configuration and operation conditions to find a way towards effective and controllable process intensification.

As shown in Fig. 4a, increasing the flow rate was beneficial to improve the mixing effect of the two phases, thereby accelerating the reaction conversion. Figure 4b shows the comparison of three different configurations at high and low capacities. Because the thick tube had a large inner diameter and was lack of extra turbulence, the two phases were easily separated and the conversion was extremely low. As for the thin coil

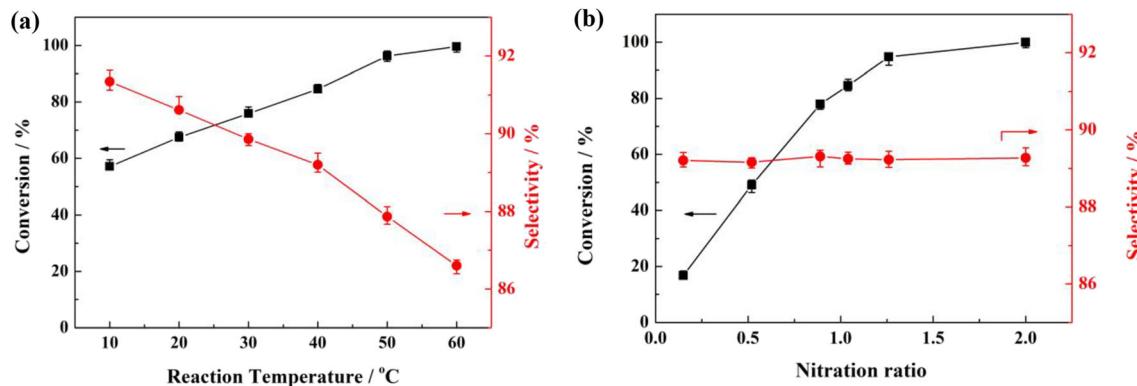


Fig. 2 Effect of (a) reaction temperature, (b) nitration ratio under isothermal conditions. Conditions: the ID of T-type micromixer, 0.25 mm; type of reaction tube, a thin tube; residence time, 160 s; molar ratio of nitric acid, sulfuric acid, and water, 1:4:0.22; and (a) nitration

ratio, 1.01; flow rate ratio of the organic and mixed acid, 1:2.44; (b) reaction temperature, 40 °C; the flow rate ratio of the organic and mixed acid varied with nitration ratio

Table 1 Reaction outcome of different feed compositions under adiabatic condition

Entry	1 in the organic/wt%	$\Delta T/^\circ\text{C}$	Calculated $\Delta H/\text{kJ/mol}$	Selectivity/%
1	100	198.2	-250.04	83.49
2	75	104.1	-156.85	86.75
3	50	72.2	-152.18	87.37
4	25	41.9	-139.15	88.97

tube, due to its small inner diameter, the initial dispersion was relatively good, but the phase separation in sequence could not be avoided (as shown in Fig. S3(a)), corresponding to a quickly decreased conversion rate. In contrast, the micropacked-bed reactor can enable and keep a microdispersion state throughout the system. As shown in Fig. S3(b), well-dispersed organic phase droplets can be obtained at the end of the micropacked-bed reactor. Even at low flow rates (1 mL/min of organic phase flow rate), the micropacked-bed reactor can still achieve effective two-phase dispersion. This difference between the liquid–liquid two-phase reaction in the micropacked-bed reactor and the thin tube was similar to what Kappe et al. [10] reported in the generation of dichlorocarbene utilizing the classical biphasic reaction of aqueous sodium hydroxide and chloroform system. Therefore, the reaction was complete in short residence time, and the reaction efficiency was greatly improved.

Figure 4c and d show the effects of the system configuration on the adiabatic nitration reaction. As we know, the micromixer mainly provides an initial two-phase dispersion. A suddenly expanded connecting tube after a T-type micromixer was beneficial to provide instantaneous and rapid mixing [13]. However, as seen from Fig. 4c, compared with

the micropacked-bed reactor, the T-type micromixer had limited influence on the reaction conversion, and the reaction is mainly completed in the micropacked-bed. As shown in Fig. 4d, the smaller the packing particles are, the sooner a complete conversion platform appeared. To achieve 90% conversion, it took about 1 s for smaller packing size (0.177–0.250 mm) and about 3 s for larger packing size (0.350–0.500 mm). But smaller particles corresponded to higher pressure drop (more details can be found in Supplementary Information). Therefore, it requires to make a compromise between the mixing performance and the system pressure drop.

Overall, through the optimization of the reaction conditions and system configuration, the nitration of **1** could proceed sufficiently within the residence time of 5 s by using an adiabatic micropacked-bed reactor. The partial product circulation could control the adiabatic reaction temperature reliably and flexibly, assuring the selectivity not less than 89%. We summarized different operation processes for comparisons, as shown in Table S2. The intensification strategy with the combination of a micropacked-bed reactor and a partial product circulation took distinct advantages in productivity, safety, and controllability (more details can be found in Table S3, Supplementary Information).

Modelling the adiabatic nitration process

For an adiabatic reaction process, the activation energy is an important parameter determining the apparent reaction kinetics. An accurate determination of the activation energy is a fundamental of process design, for which a common method is to carry out a serial of isothermal reactions under different temperatures. However, since the nitration reaction is relatively violent and the absolute isothermal reaction conditions cannot be well controlled, this method does not work well. Besides, the acquisition of kinetic data under isothermal condition usually needs complicated sampling procedures and chemical analysis, bringing high cost and low efficiency. Herein, we attempted to rapidly obtain the kinetic parameters under adiabatic conditions by interpreting the profile of temperature along the flowing direction [36]. Based on the above reaction kinetic characteristics, it could be assumed that the reaction kinetics is almost controlled by the micropacked-bed reactor. The experimental data (those adopted at the organic phase flow rate of 6 mL/min) was processed with the

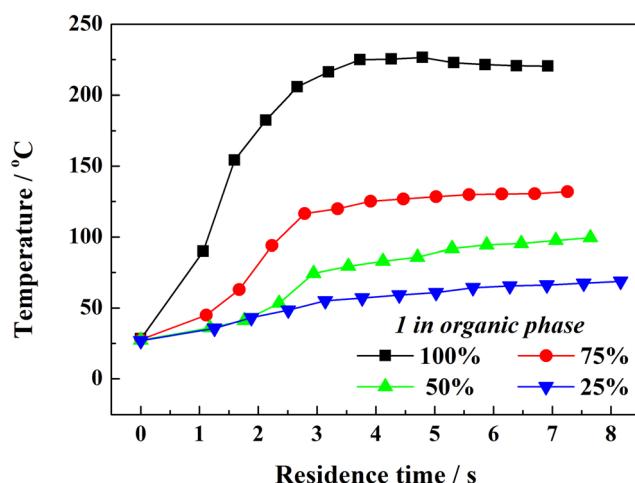


Fig. 3 Temperature distribution under different feed composition. Reaction conditions: the molar ratio of organic feed (**1** + **2**) and sulfuric acid, 1:4; nitration ratio, 1.1; flow rate ratio of the organic and mixed acid, 1:2.13; preheat temperature, 27.5 °C; type of reaction tube, a micropacked-bed reactor, filled with glass beads (φ , 0.177–0.250 mm); the ID of T-type micromixer, 0.25 mm

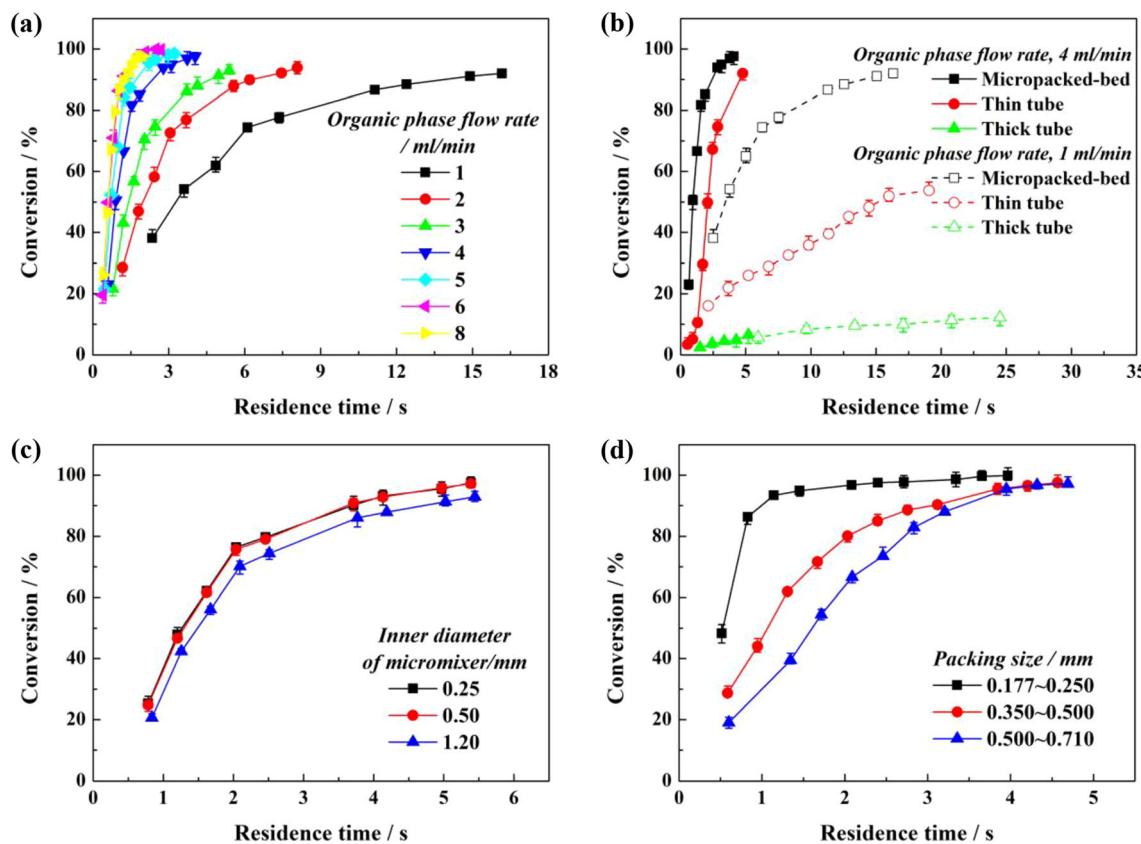


Fig. 4 Time profiles of conversion under adiabatic conditions. Reaction conditions: mass ratio of organic phase, **1**:**2**=1:3; the molar ratio of organic feed (**1**+**2**) and sulfuric acid, 1:4; nitration ratio, 1.1; flow rate ratio of the organic and mixed acid, 1:2.13; preheat temperature, 30 °C; the type of reaction tube, a micropacked-bed reactor. **a** and **b**, the ID of T-

type micromixer, 0.25 mm; packing size of the micropacked-bed reactor, 0.177–0.250 mm. **c** packing size, 0.177–0.250 mm; organic phase flow rate, 3 mL/min. **d** the ID of T-type micromixer, 0.25 mm; organic phase flow rate, 4 mL/min

assumption that the two-phase flow state did not change much throughout the micropacked-bed reactor. Thus, the reaction activation energy could be rapidly obtained by fitting, and the influence of the initial temperature on the reaction kinetics could be predicted as a basis of designing an adiabatic reaction process and reactor.

In detail, according to the kinetic models of similar aromatics nitration reactions reported in the literatures [4, 18, 22, 30], we assumed that nitration is a second-order reaction which is the first order with respect to both aromatic and nitric acid. Thus, the reaction rate can be expressed as follows:

$$-r = -\frac{dC_1}{dt} = kC_1 C_{\text{HNO}_3} \quad (1)$$

Considering $C_1 = C_{1,0}(1-X)$ and $C_{\text{HNO}_3} = C_{1,0}(M-X)$, Eq. 1 can be transformed into the integral form:

$$\frac{dX}{dt} = kC_{1,0}(1-X)(M-X) \quad (2)$$

where M is the nitration ratio. And $C_{1,0}$ is the initial concentration of **1** calculated by Eq. 3:

$$C_{1,0} = \frac{\omega\rho V_{\text{organic}}}{M_1(V_{\text{organic}} + V_{\text{mixed acid}})} \quad (3)$$

where V_{organic} and $V_{\text{mixed acid}}$ are the flow rates of organic phase and acid phase respectively, and supposed the total volume of the two fluids remained unchanged after mixing; ω is the mass fraction of **1** in the organic phase; ρ is the density of the organic phase; and M_1 is the molar mass of **1**.

Table 2 Calculation results of kinetic parameters under different preheating temperatures

Entry	Preheating temperature/°C	Ea/kJ/mol	R ²
1	25	31.40	0.9848
2	30	30.76	0.9859
3	35	31.26	0.9823
4	40	30.09	0.9812
5	45	31.30	0.9899

The formula for the reaction heat was shown below:

$$\Delta H_m = \frac{(\sum m c_p) \times \Delta T}{n_1 X} \quad (4)$$

where ΔH_m is reaction heat; c_p is the heat capacity of the fluid; m is the mass flow rate of the substance; ΔT is the reaction temperature rise; n_1 is the molar flow rate of **1**.

We further assumed that the reaction was irreversible, the reaction system was completely insulated; and the density, heat capacity, and enthalpy did not change during the reaction proceeding. The relationship between conversion X and temperature rise ΔT can be described as:

$$X = \frac{\Delta T}{\Delta T_{max}} \quad (5)$$

where ΔT_{max} is the reaction temperature rise corresponding to complete conversion. According to the Arrhenius equation $k = Ae^{-E_a/RT}$ and Eq. 5, Eq. 2 can transform into the following form:

$$\frac{1}{\Delta T_{max}} \frac{dT}{dt} = Ae^{-E_a/RT} c_{1,0} \left(1 - \frac{\Delta T}{\Delta T_{max}}\right) \left(M - \frac{\Delta T}{\Delta T_{max}}\right) \quad (6)$$

Take the natural logarithm on both sides to get the following form:

$$\begin{aligned} \ln\left(\frac{1}{\Delta T_{max}} \frac{dT}{dt}\right) - \ln\left(1 - \frac{\Delta T}{\Delta T_{max}}\right) - \ln\left(M - \frac{\Delta T}{\Delta T_{max}}\right) \\ = \frac{-E_a}{RT} + \ln A + \ln c_{1,0} \end{aligned} \quad (7)$$

Thus, the kinetic parameters can be obtained by linear fitting.

Figure 5a shows the experimental results and the polynomial fitting curve at a preheating temperature of 25 °C. Further derivation can calculate the term of $\frac{dT}{dt}$. Next, by linearly fitting $\ln\left(\frac{1}{\Delta T_{max}} \frac{dT}{dt}\right) - \ln\left(1 - \frac{\Delta T}{\Delta T_{max}}\right) - \ln\left(M - \frac{\Delta T}{\Delta T_{max}}\right)$ and $\frac{1}{T}$ (as shown in Fig. 5b), the kinetic parameters can be gained. At this

preheating temperature, the calculated Ea is 31.40 kJ/mol, and R^2 is 0.9848. The kinetic parameters calculation results under different preheating temperatures were provided in Table 2. At different preheating temperatures, the calculated kinetic parameters were similar and the experimental data and the calculated data at different preheating temperatures were well consistent with each other, as shown in Fig. 5c. It indicated that this model exhibited a satisfying fit to the experimental data. And the calculated Ea of this nitration reaction is 30.96 ± 0.87 kJ/mol. Using this method, the reaction kinetic parameters can be conveniently obtained through temperature distribution measurement under the adiabatic reaction condition.

Conclusions

The nitration reaction of *o*-dichlorobenzene (**1**) with mixed acid, a rapid and highly exothermic reaction, was conducted in continuous-flow reactors to produce the dye intermediate 3,4-dichloronitrobenzene (**2**). The reaction kinetic characteristics were explored under different micro-dispersion methods like a thin capillary coil microreactor and a micropecked-bed reactor. The strategy in terms of combining the adiabatic nitration, the utilization of a micropacked-bed reactor, and introducing partial product circulation, was verified to achieve the matching of the micro-dispersion state and the reaction kinetic characteristics. Through temperature measurement at different positions of the reaction tubes under adiabatic temperature, the reaction process could be carefully monitored. The micropacked-bed reactor can maintain a better two-phase dispersion to make the reaction proceed thoroughly within 5 s or less residence time under adiabatic condition, and the selectivity can keep at 89% or higher. Furthermore, we developed a method for the rapid determination of activation energy by processing the profile of adiabatic temperature rise. The activation energy Ea of this nitration reaction was determined to be 30.96 ± 0.87 kJ/mol, which may enable a reliable design for a high-efficiency nitration reaction process with the

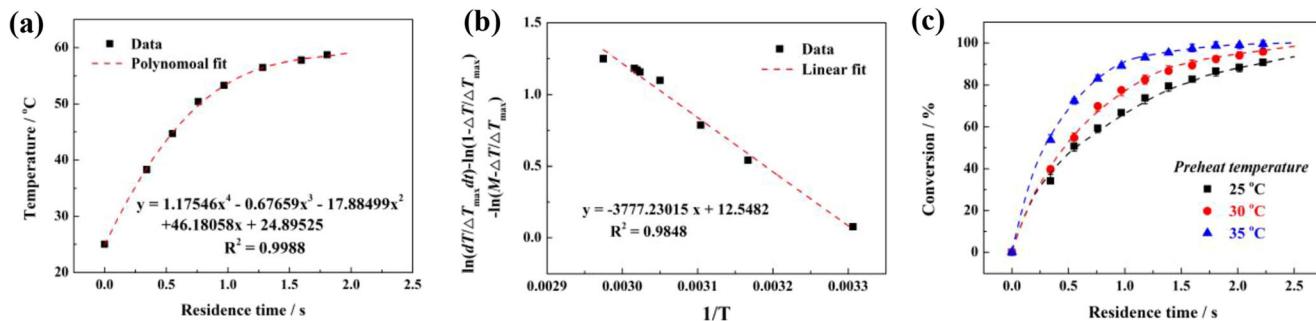


Fig. 5 **a** Curve of temperature vs. residence time and polynomial fitting line; **b** linear fitting for kinetic parameters; **c** experimental data (filled circles) and model data (dashed line) at different preheating temperatures and residence times. Reaction conditions: mass ratio of

organic phase, **1**: **2** = 1:3; the molar ratio of organic feed (**1** + **2**) and sulfuric acid, 1:4; nitration ratio, 1.1; flow rate ratio of the organic and mixed acid, 6:12.8; the ID of T-type micromixer, 0.25 mm; packing size of the micropacked-bed reactor, 0.177–0.250 mm

introduction of partial product circulation and micropacked-bed reactor.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s41981-020-00132-3>.

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Authors' contributions Not applicable.

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Data availability Not applicable.

Compliance with ethical standards

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Code availability Not applicable

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