Kinetic Study of Reactions of Aniline and Benzoyl Chloride in a Microstructured Chemical System

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DOI 10.1002/aic.14891

The reaction between aniline and benzoyl chloride is well known for producing high performance polymers and chemicals. But the fast main reaction and reversible consecutive side reaction make process rather complicated and no thorough kinetics study has ever been reported before. A microstructured chemical system, consisting of a micromixer, preheat exchange coiled capillaries, a delay loop, and a microhydrolyzer, was designed to carry out this reaction using N-methyl-2-pyrrolidone as the solvent. A kinetic model was established, and the values of kinetic constants, pre-exponential factors and activation energies of each reaction as well as their confidence intervals were acquired. With this model each substance concentration vs. residence time were obtained to help understand reaction process and further optimize operating conditions. Compared to earlier reports on this reaction, this microstructured chemical system provides more accurate parameters and can develop a reliable platform for kinetic study of similar chemical reactions.

Keywords: kinetics, aniline, benzoyl chloride, N-methyl-2-pyrrolidone, microstructured chemical system

Introduction

Kinetic study of the reaction between aniline (AL) and benzoyl chloride (BC) is very appealing and important since it reveals the intrinsic rules of reactions between aromatic amines and aromatic acid chlorides, a fundamental chemical step in organic synthesis and polymerization process.[1,2] For example, a deep understanding of kinetics of the reactions between AL and BC can be very helpful to characterize the polycondensation speed of *p*-phenylenediamine (PPD) and terephthaloyl chloride (TPC) for the preparation of poly(*p*-phenylene terephthalamide) (PPTA), a high performance material with high tensile and toughness, light weight, and excellent corrosion resistance, which is widely used in bulletproof, aircraft, asbestos replacement, and so on.[3,4] Another example is benzanilide (BA), the product of the reaction between AL and BC, which is a widely used intermediate for the production of insecticides, spice, and medicine.[5,6] Nevertheless, the direct intrinsic kinetic study of this kind of reaction is very difficult because of the complicacy and variability of the reaction system.[7,8]

Figure 1 shows the reactions between AL and BC. Besides the main reaction, there is a reversible consecutive side reaction between the by-product HCl and AL. According to literature,[9] the main reaction has a rate constant (k_1) of 128 L $\text{mol}^{-1}\ \text{s}^{-1}$ at 25°C, and it is so rapid that the reaction condition of fast mixing and accurate residence time control are required. However, it is quite difficult to reach these conditions in traditional stirred tank reactors. The rapid conjugation reaction and the reversible consecutive side reactions are the common characteristics of all these similar processes. The by-product decomposition rate is rather slow compared to the main reaction, resulting in the converting speed of reactants decreasing dramatically in later stage, and the reaction network seems "slow" as a whole. Therefore, the kinetic study is of great importance to regulate processes for these kinds of similar reactions. But it is noted that the highly coupled reactions with different reaction rates makes such kinetic study quite difficult.

As an important reaction, the kinetic study of the reactions between AL and BC has attracted many researchers' interest.[9–12] Borkent et al. studied the reactions of aromatic amines and acid chloride in hexamethylphosphoric triamide using a stopped-flow spectroscopy method.[9] By changing the substituents of the aromatic amines and acid chloride, the influence of the substituents on the kinetics was analyzed by Hammett relations. However, as the author admitted, the results might not be very accurate because five parameters had to be estimated from a single curve. Wamser et al. determined the kinetics and mechanisms of the two-phase reactions between aqueous AL and BC in chloroform.[10] In their study, the reactions were limited by the transfer of AL from the aqueous phase to the organic phase. Overall, the fast main reaction makes it quite difficult to study the kinetics in traditional stirred reactors. Moreover, in the polycondensation process, high conversions of reactants are highly required for the preparation of polymers with high average molecular weight. Thus, more studies on the reaction kinetics between AL and BC in N-methyl-2-pyrrolidone (NMP) should be done for better control and optimization of the reaction condition.

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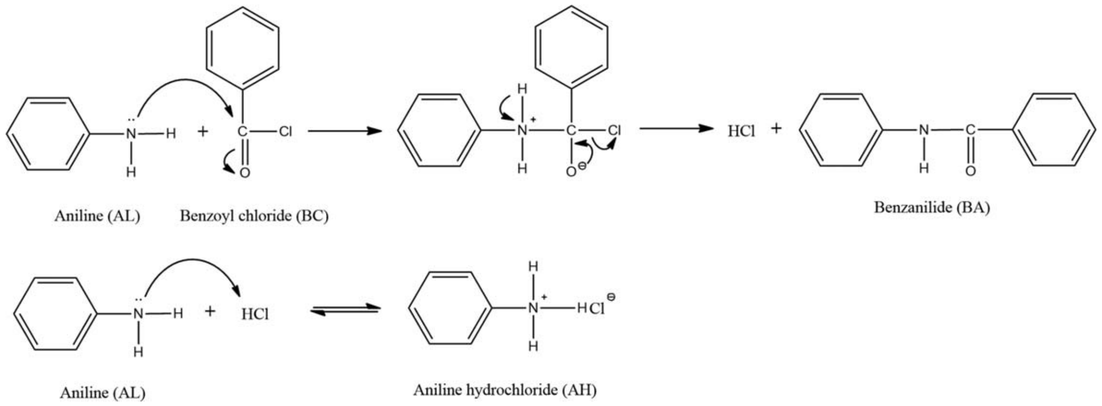

Figure 1. The reactions between aniline and benzoyl chloride.

Microreactor has been an attractive tool for kinetics measurements in these days,[13–15] because of its superior advantages in enhanced mixing ability,[16] accurate control of reaction temperature,[17] and residence time,[18] minute consumption of reagents,[19] essential safety,[20] and so on. More precise kinetic parameters are expected to be obtained using a microreactor, especially for fast reactions.[21,22] A number of reaction processes have been successfully conducted in microreactors, such as, cyclohexanone ammoximation over TS-1 catalyst,[23] fast exothermic premixing reactions,[21] dehydrochlorination of dichloropropanol,[24] Diels–Alder reactions,[25] and synthesis of sodium nitrotetrazolate (NaNT).[26] But the kinetic study of complex systems like AL and BC using microreaction technique has not ever been reported.

In this article, a microchemical system, which is composed of a micromixer, preheat exchange coiled capillaries, a delay loop and a microhydrolyzer, has been designed to study the kinetics of the reactions between AL and BC. The objective of this work is to study the kinetics accurately and establish an intrinsic kinetic model on the basis of mechanism understanding and process intensification. A reasonable reaction network mechanism was verified and a kinetic model has been established. By taking advantages of the rapid mixing and accurate temperature and residence time control of the microstructured chemical system, experiments in different residence time spans have been designed elaborately, and all the reactions kinetics parameters, including the orders of the reactions, rate constants, pre-exponential factors and activation energies as well as their confidence intervals have been determined.

Experimental

Materials

AL (99.5%), BC (99%), and BA (98%) were purchased from J&K Scientific (Beijing); NMP (>99%) was from Aladdin Industrial (Shanghai). The trace water in NMP was removed by adding NMP in molecular sieve and CaH_2 before the experiments.

Equipment

The schematic diagram of the microchemical system is shown in Figure 2. The AL/NMP solution and the BC/NMP solution were delivered from two glass vessels and then separately pumped into stainless steel capillaries (316 stainless steel) by two metering pumps (Beijing Satellite Co.). The solutions were preheated to reaction temperature in coiled stainless capillaries before they were mixed violently in the microsieved dispersion mixer (316 stainless steel). All the capillaries have an inner diameter of 2 mm and an external diameter of 3 mm. The schematic diagram of the micromixer is shown in Figure 3 and the mixing performance of the micromixer has been reported in our previous work.[27] The microsieved pore is a square with 0.4 mm of side length and the crossflow channel is 10 mm in length, 0.4 mm in width, and 0.4 mm in height. Ideal mixing was achieved in the micromixer when the total flow rate was large enough. A stainless delay loop with an inner diameter of 2 mm was connected directly to the outlet of the micromixer. The reactions between AL and BC took place in the delay loop and this delay loop reactor was assumed as a plug flow reactor. The reaction residence time could be controlled precisely by

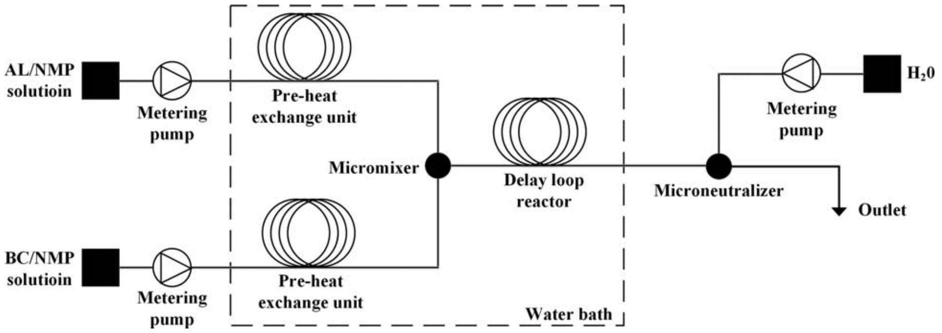

Figure 2. The schematic overview of the experimental setup.

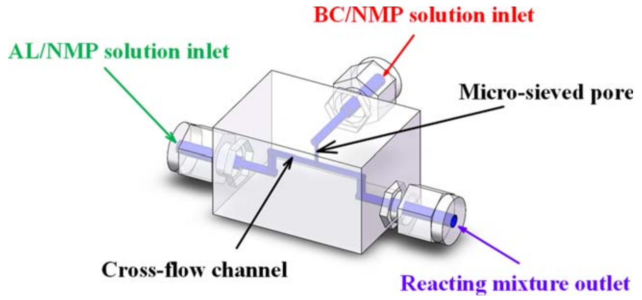

Figure 3. The 3-D structure of the micromixer.

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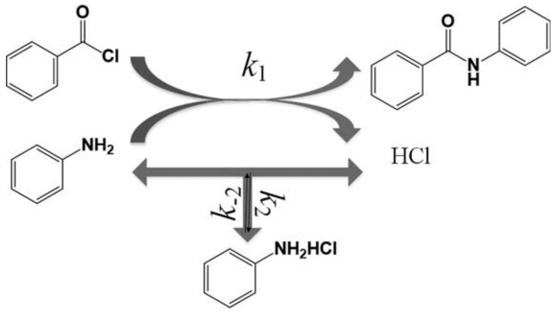

Figure 4. The pathway of each reactants.

changing the length of the delay loop and the flow rate of the solutions. All the preheat exchange units, the micromixer, and connected delay loop were immerged in a water bath to control the reaction at a certain temperature. The reaction was quenched in the microneutralizer using enough ultrapure water because benzoic acid, the product of BC and H_2O, has much lower reaction activity than BC and the reaction between benzoic acid and AL could be ignored in a rather short time. The construction of the microneutralizer is the same as the micromixer. Samples were collected at the outlet and then were analyzed as soon as possible.

Analysis

As NMP and water are miscible, the collected samples were homogeneous. A high performance liquid chromatography (HPLC, Agilent 1100) with an ultraviolet detector was used to analyze sample contents under the following conditions: C18 chromatographic column; 60% HPLC acetonitrile and 40% ultrapure water as mobile phase; mobile phase flow rate 1 mL/min; detection wavelength at 280 nm. The yield of BA (Y) is calculated by the following equations

$$Y=\frac{C_{\mathrm{BA}}\times F_{\mathrm{t}}}{C_{\mathrm{AL}}\times F_{\mathrm{AL}}} \tag{1}$$

where C_{BA} (mol/L) is the concentration of BA in the collected sample; F_{t} (mL/min) is total flow rate including AL solution, BC solution, and ultrapure water; C_{AL} (mol/L) is the initial concentration of AL solution; F_{AL} (mL/min) is the flow rate of AL solution. By repeating the reactions 3 times under the same condition, the relative measurement error of the yield was decreased to 1%.

Results and Discussion

Verification of the reactions between AL and BC

The reactions between AL and BC have been reported in literature,[9] as shown in Figure 1. Figure 4 describes the pathways of each substance in the reaction process. The following facts could support the proposal.

1. Polymers linked by amide bonds, such as PPTA, have excellent corrosion resistance property so the reaction between AL and BC must be irreversible;
2. AL is an organic base and is supposed to react with HCl;
3. High average molecular weight PPTA can be prepared when the molar ratio of PPD and TPC is nearly 1:1,[5] so the reaction between AL and HCl is reversible. Aniline hydrochloride (AH) should be an intermediate.

To further verify the above reaction pathways, some experiments were performed in the microstructured chemical system and in an Erlenmeyer flask, respectively. The reaction between AL and BC and the reaction between AL and HCl were found to be so rapid that nearly 90% of the reactants were consumed within less than 0.1 s and the yield of BA stayed steady in the time span of around 1 s when the concentration was 0.6 mol/L, as shown in Figure 5a. The side reaction was further verified by changing the orders of adding AL/NMP solution and BC/NMP solution. When the BC solution was added into the AL solution, the by-product HCl reacted with the redundant AL easily, resulting in 100% BA yield time delaying, as show in Figure 5b. The final 100% BA yield indicates the side reaction is reversible. The decomposition of AH is a relative slow process that the 100% BA yield could be obtained at 10 min or even several hours. That is to say, the reaction between AL

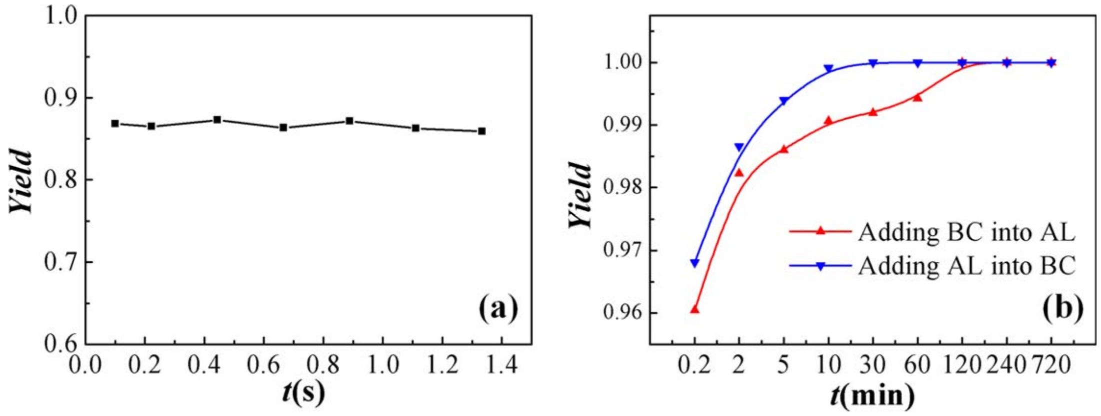

Figure 5. Verification of the reaction mechanism.

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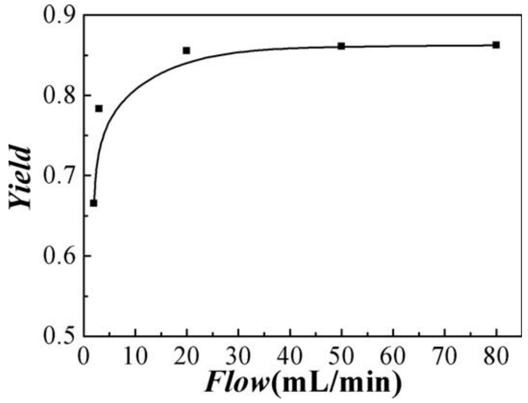

Figure 6. Ideal mixing is achieved when flow rate is large enough.

and BC and the reaction between AL and HCl are much faster than the decomposition of AH, and parameters of the former two reactions and the last reaction should be obtained separately. In our study, parameters of the former two reactions were obtained by conducting the reactions in the time span of around 1 s first. After getting the parameters of fast reaction, parameters of the last slow reaction was then obtained by conducting the reaction in the time span of several minutes.

Determination of k_1 and k_2

A model approaching the intrinsic kinetics is expected to be established to describe the reaction process. The following considerations are thought to be reasonable in building the kinetic model:

1. Ideal mixing is achieved when the flow rate is larger than 20 mL/min according to our previous study on the mixing ability of the micromixer, as shown in Figure 6. The segregation indexes, X_S, is in the range of $10^{-2}-10^{-3}$, which indicates high mixing efficiency has been achieved in the micromixer[27] and nearly ideal mixing is expected to be achieved when the flow rate is high enough. According to literature report, it is assumed that there is no back mixing in the delay loop and the residence time of the reaction could be equal to the time that the reaction mixture stayed in the delay loop.[28,29]

2. The reaction between AL and BC and the reaction between AL and HCl are much faster than the decomposition of AH, and the decomposition reaction could be ignored in the time span of around 1 s. This assumption is based on the results in Figure 5;

3. According to literature, all the reactions are in first-order with respect to each reactant.[9]

So the kinetic model in the time span of around 1 s is as follows

$$\frac{dC_A}{dt}=-k_1C_AC_B-k_2C_AC_D \tag{2}$$

$$\frac{dC_B}{dt}=-k_1C_AC_B \tag{3}$$

$$\frac{dC_C}{dt}=k_1C_AC_B \tag{4}$$

$$\frac{dC_D}{dt}=k_1C_AC_B-k_2C_AC_D \tag{5}$$

$$\frac{dC_E}{dt}=k_2C_AC_D \tag{6}$$

where the subscripts A, B, C, D and E stand for AL, BC, BA, HCl, and AH, respectively.

The results may be less accurate or even incorrect if multiple parameters are obtained from a single curve. So in this work, each curve was used to obtain only one parameter or one relationship between different parameters. Since the purpose of this work is to study the kinetics of the reaction between AL and BC to help characterize the polycondensation of PPD and TPC, the reaction conditions were chosen according to the actual industrial process conditions for the preparation of PPTA. Low temperature reactions below 100°C and preferably below 50°C are desirable.[30,31] Here the effects of the molar ratio of BC and AL (*M*-ratio) on the yield of BA was used to obtain the ratio of k_2 and k_1, as shown Figure 7a. From this result, the regression value of k_2/k_1 is 0.118, and 95% confidence interval is 0.068–0.167. The calculated data fit well with the experimental data. When molar ratio of BC and AL is kept at 1:1, temperature changes have little effect on the BA yield, especially in the range of 0–40°C, as shown in Figure 7b, which means the value of k_2/k_1 has little to do with temperature in the experimental conditions. The reaction between AL and BC and the reaction between AL and HCl have similar activation energies. Effects of temperature on the rates of these two reactions are similar, resulting in nearly unchanged value of k_2/k_1. The values of activation energies of these two reactions later in this article would prove this point.

After getting the relationship between k_1 and k_2, there is only one parameter in the kinetics model equivalently. The reaction between AL and BC is too rapid to catch the yield changes vs. time at high reactants concentration. However, the total order of the reaction between AL and BC is 2, so the

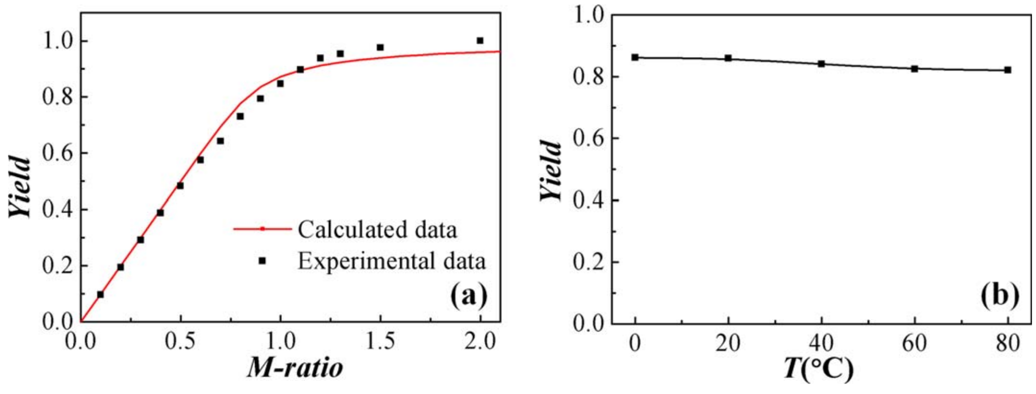

Figure 7. Reaction performance in the microstructured chemical system.

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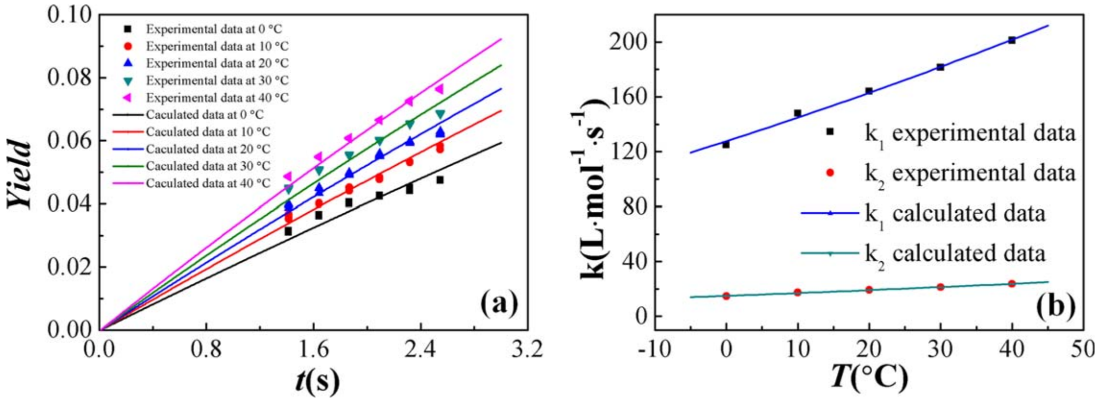

Figure 8. Determination of k_1 and k_2 in the microsystem.

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reaction rate becomes slower when the reactants concentration is decreased according to classical reaction kinetics principle. The experiments were conducted at lower reactant concentration of 1.69×10^{-4} mol/L in our study to trace the change of yield more accurately. Values of k_1 and k_2 at different temperatures were then obtained using BA yield over residence time curves, as show in Figure 8a. From the diagram, the calculated data fit well with the experimental data at each temperature. The regression values and 95% confidence intervals of k_1 and k_2 are shown in Table 1. The value of k_1 at 20°C obtained in this work is 163.9 L $\text{mol}^{-1}\text{s}^{-1}$ while the literature value is 128 L $\text{mol}^{-1}\text{s}^{-1}$ at 25°C.[9] The kinetics parameter determined in the microstructured chemical system is a little larger than that got in the traditional way. The parameter obtained in the microstructured chemical system is believed more accurate because of its enhanced mixing efficiency, precise residence time, and temperature control, especially for rapid reactions just like the reaction between AL and BC in the time span of around 1 s. After getting k_1 and k_2 at different temperature, the pre-exponential factors and activation energies of these two reactions have been regressed using the Arrhenius equation, as shown in Figure 8b. The values and confidence intervals of pre-exponential factors and activation energies are shown in Table 2. The pre-exponential factor and activation energy of the reaction between AL and BC are first reported as we have known.

Determination of k_{-2}

After getting values of k_1 and k_2 at different temperatures, the decomposition rate constant of AH k_{-2} should be got before an integral reaction network kinetics could be established. By extending the time span to several minutes, the whole kinetics network is completed as follows

$$\frac{dC_A}{dt} = -k_1C_AC_B - k_2C_AC_D + k_{-2}C_E \tag{7}$$

$$\frac{dC_B}{dt} = -k_1C_AC_B \tag{8}$$

$$\frac{dC_C}{dt} = k_1C_AC_B \tag{9}$$

$$\frac{dC_D}{dt} = k_1C_AC_B - k_2C_AC_D + k_{-2}C_E \tag{10}$$

$$\frac{dC_E}{dt} = k_2C_AC_D - k_{-2}C_E \tag{11}$$

where the subscripts A, B, C, D, and E stand for AL, BC, BA, HCl, and AH, respectively.

By changing the residence time in the span of several minutes, k_{-2} could be regressed using the BA yield over residence time curve and the calculated data fit well with the experimental data, as shown in Figure 9a. The value of k_{-2} is 6.4×10^{-3} s^{-1} and 95% confidence interval is 5.4×10^{-3}–7.3×10^{-3} s^{-1} at 0°C. After getting k_{-2} values at different temperature, the pre-exponential factor (A_{-2}) and activation energy (E_{-2}) of the decomposition reaction of AH could be obtained, as shown in Figure 9b. The values and 95% confidence intervals are shown in Table 3. There was only thermodynamic data about the balance between AL, hydrogen ion, and AH that have been reported before, and the kinetics data about the decomposition of AH and reaction between AL and HCl are the first time to be reported as we know.

After all the parameters are obtained, a complete kinetic model can be established. Changes of each substance concentration of different time span are shown in Figure 10. When the reactants concentration is 0.2 mol/L, nearly 90% of the reactants are consumed in less than 0.6 s and the yield of BA seems steady in the time span of around 1 s. However, when the residential time is extended to 500 s, the yield of BA increases gradually with the decomposition of AH. From this simulation result, our assumption that the decomposition of AH could be ignored in the time span of around 1 s has been further proved to be reasonable. The concentration change over time exhibited here is expected to help understand the

Table 1. Values and Confidence Intervals of k_1 and k_2 at Different Temperature

Temperature (°C)	Values of k_1 (L $\text{mol}^{-1}\text{s}^{-1}$)	k_1 confidence intervals	Values of k_2 (L $\text{mol}^{-1}\text{s}^{-1}$)	k_2 confidence intervals
0	124.9	120.8–128.9	14.7	14.2–15.1
10	147.9	143.4–152.3	17.4	16.9–17.9
20	163.9	159.7–168.2	19.3	18.8–19.8
30	181.4	177.3–185.6	21.3	20.8–21.8
40	201.2	197.7–204.7	23.6	23.2–24.1

Table 2. Values and Confidence Intervals of the Pre-Exponential Factors and Activation Energies of k_1 and k_2

Factors	Values	Confidence intervals
E_1 (kJ/mol)	8.14	7.03–9.26
A_1 (L $\text{mol}^{-1}\text{s}^{-1}$)	4.60×10^3	2.52×10^3–6.69×10^3
E_2 (kJ/mol)	8.14	7.03–9.26
A_2 (L $\text{mol}^{-1}\text{s}^{-1}$)	5.41×10^2	2.96×10^2–7.86×10^2

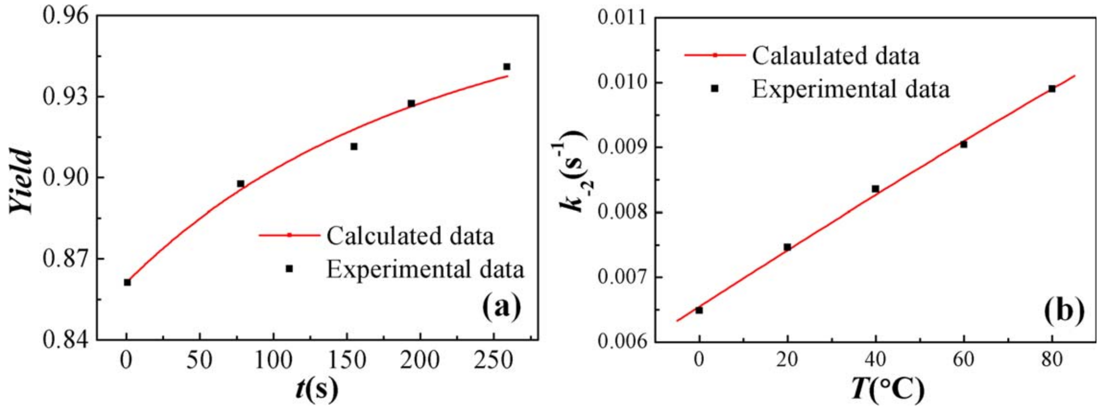

Figure 9. Determination of k_{-2} in the microsystem.

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Table 3. Values and Confidence Intervals of the Pre-Exponential Factor and Activation Energy of k_{-2}

Factors	Values	Confidence intervals
E_{-2} (kJ/mol)	4.14	3.77–4.52
A_{-2} (s^{-1})	4.07×10^{-2}	3.49×10^{-2}–4.65×10^{-2}

whole process better. The complete reaction kinetic model could also be used to simulate other situations. For example, it could be modified by adjusting the amount of HCl remaining in the reaction system when a basis is present since the acid–base neutralization reaction is nearly instantaneous.

Reaction kinetics network verification and optimization

The reaction kinetics network has been verified by changing the reactant concentration, as shown in Figure 11. The calculated data fit well with the experimental data in a large concentration range of 5×10^{-5}–3×10^{-1} mol/L.

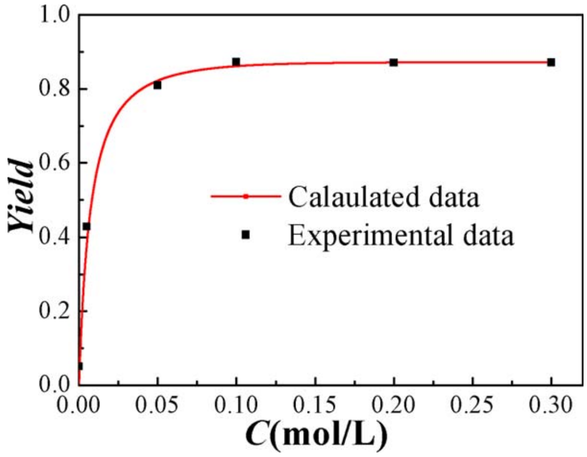

Figure 11. Effects of reactants concentration on the yield of benzanilide.

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Furthermore, the kinetic model was used to optimize the operating conditions. As we all know, high monomers conversion is an essential condition for the preparation of polymers with high average molecular weight in the polycondensation of aromatic amines and aromatic acid chlorides process. Hence, high reactants conversion is a key point in the study. Using the kinetic model developed earlier, we have obtained the reaction time for 99% reactants conversion under the conditions of 2.0×10^{-4}–2.0×10^{-1} mol/L of reactants concentration and temperatures at 0, 20, 40, 60, and 80°C, as shown in Figure 12. Time for 99% reactant conversion is about half an hour when the temperature is 0°C and at higher concentration, but it increases dramatically when the concentration gets below 2.0×10^{-3} mol/L. When temperature is higher, time

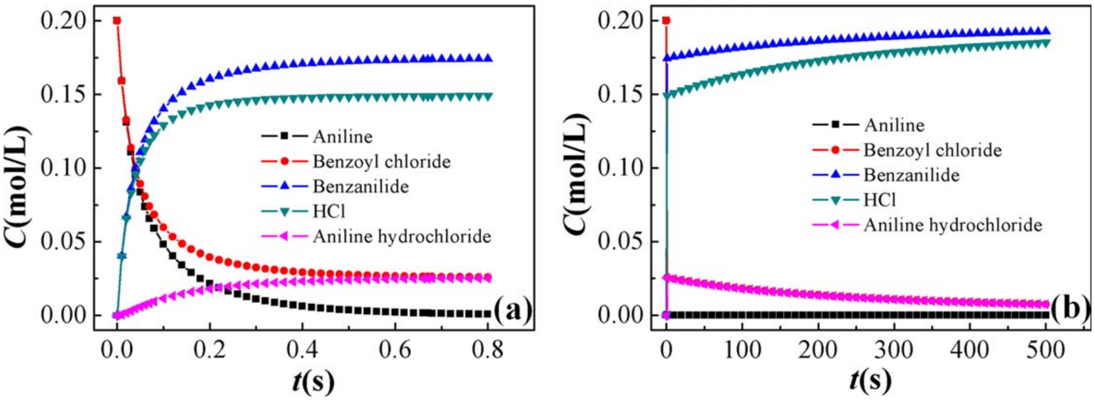

Figure 10. Simulation results of concentration of each substance changes vs. time.

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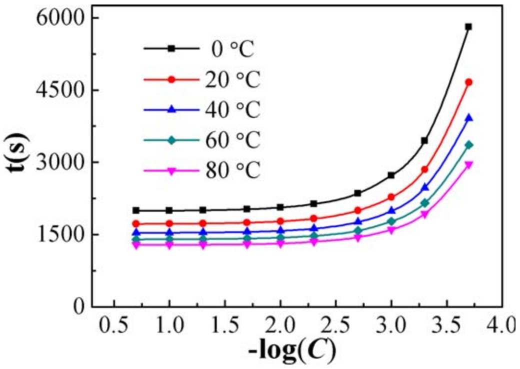

Figure 12. Time required for 99% conversion rate.

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for 99% reactant conversion gets shorter. For example, time for 99% reactants conversion at 60°C is about 10 min less than that at 0°C. According to our simulation results, reactants concentration higher than 0.002 mol/L and higher temperature are recommended to make the polycondensation of aromatic amines and aromatic acid chlorides faster. Of course, the process should also be conducted in a controllable range.

Conclusion

In this work, a microstructured chemical system has been successfully designed for the kinetic study of the reactions of AL and BC in NMP. The reaction network including a reversible consecutive side reaction has been verified. The reaction kinetics have been investigated in the residence time span of around 1 s and several minutes for the determination of different reaction rate constants. Rate constants which are of a difference of 4–5 orders of magnitude have been obtained accurately in this way. A complete kinetic model has been established to describe this reaction network and the reaction rate constants, pre-exponential factors and activation energies as well as their confidence intervals of each reaction have been obtained. This model first reported the pre-exponential factor and activation energy of the reaction between AL and BC and the kinetics data about the decomposition of AH and reaction between AL and HCl, and it can be applied to processes with similar reaction mechanism. Changes of each substance concentration vs. residence time have been calculated using this model to help understand the whole process deeply. Furthermore, the reaction kinetic network model has also been used to optimize the operating conditions, and it is expected to guide the polymerization process of aromatic amine and aromatic acyl chloride in our future work.

Acknowledgment

The authors gratefully acknowledge the supports of the National Natural Science Foundation of China (Nos. U1463208 and 91334201) on this work.

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Manuscript received Mar. 27, 2015, and revision received May 10, 2015.