

Synthesis, Optimization, and Thermal Risk Analysis of One-Pot **N-Nitrodiethanolamine Dinitrate Synthesis**

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S Supporting Information

ABSTRACT: N-Nitrodiethanolamine dinitrate (DINA) is a nitramine explosive containing both O-nitro and N-nitro groups. In this work, the synthesis of DINA by nitration of diethanolamine hydrochloride (DEAHC) with the fuming nitric acid/acetic anhydride (HNO₃/Ac₂O) system was developed and optimized. It was found that large amounts of acetic anhydride and low reaction temperature are favorable to the yield of DINA. When the DEAHC:HNO3:Ac2O molar ratio was 1:4.5:6 and the initial reaction temperature was decreased to 5 $^{\circ}$ C, the yield of DINA reached ~92%. The thermal risk of this synthesis route was also analyzed. The value of T_{D24} for the final reaction mixture was calculated to be 61.9 °C, which is significantly higher than the MTSR for the synthesis process. This indicates that as long as the addition immediately stops in case of the cooling failure scenario, decomposition of the formed DINA will not occur. The above analysis shows that the DINA synthesis approach reported here is favorable in terms of both productivity and safety.

KEYWORDS: N-nitrodiethanolamine dinitrate, exothermic reaction, thermal risk, optimization, nitramine explosive

1. INTRODUCTION

N-Nitrodiethanolamine dinitrate (DINA) is an energetic material containing one nitramine (N-nitro) group and two nitrate ester (O-nitro) groups. DINA has been widely used as a raw material to produce propellants. The study of applications of DINA can be tracked back to the Second World War.¹

The most popular route to synthesize DINA is nitration of diethanolamine (DEA) with fuming nitric acid as the nitrating agent. For this synthesis route, it has been widely considered that O-nitration is followed by N-nitration,²⁻⁵ as shown in Scheme 1. There are two classical approaches for the synthesis

Scheme 1. Traditional Synthesis Route for DINA by Nitration of DEA



of DINA by nitration of DEA: the nitric acid/acetic anhydride (HNO₃/Ac₂O) approach⁶ and the nitric acid/magnesium oxide (HNO₃/MgO) approach.⁶ For these two approaches, a chloride catalyst is required to promote N-nitration of diethanolamine dinitrate (DIA), 7 which is formed by Onitration of DEA. Ac₂O and MgO in these two approaches are used as the dehydrating agent. The most classical synthetic approach for DINA was the nitration of DEA by the HNO₃/ Ac₂O system with zinc chloride as the catalyst.⁸ The HNO₃/ Ac₂O system for the production of DINA is widely used in

Europe and the U.S.. However, in Russia and China, the HNO3/MgO system with NaCl as the catalyst is more popular.9

The disadvantage of the synthesis route in Scheme 1^6 is the separation of the O-nitration and N-nitration processes, which results in the formation of large amounts of the dangerous intermediate DIA.¹⁰ It has been experimentally determined by Zhou that the thermal stability of DIA is lower than that of DINA.⁶ From the inherent safety point of view, the accumulation of DIA should be avoided. In addition, for the HNO_3/MgO nitration system, the formation of $Mg(OH)_2$ in the O-nitration liquid system may make the reaction mixture sticky, which is unfavorable to the heat removal efficiency. This is a dangerous situation in the reaction course.⁹

To deal with the disadvantages of the synthesis route in Scheme 1, a one-pot synthesis of DINA by nitration of diethanolamine hydrochloride (DEAHC) was developed in this work. The synthesis route is illustrated in Scheme 2. Ac₂O is used as both the solvent and the dehydrating agent. The synthesized DINA was characterized by Fourier transform





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infrared spectrometry (FTIR), ¹H nuclear magnetic resonance spectroscopy (¹H NMR), and high-performance liquid chromatography (HPLC). Combined with thermal risk analysis, the results experimentally prove that this synthesis route can synthesize DINA both safely and productively.

2. EXPERIMENTAL SECTION

2.1. Materials. Diethanolamine hydrochloride with a purity of 95% was purchased from Nanjing Juyou Scientific Equipment Co., Ltd. Fuming nitric acid with a purity of \sim 97.2% was purchased from Sinopharm Chemical Reagent Company. Acetic anhydride with a purity of \sim 98.0% was purchased from Shanghai LingFeng Chemical Reagent Co., Ltd. All of the chemicals were used without further purification.

2.2. Apparatus. 2.2.1. Reaction Calorimetry. The reaction calorimeter (RC1e) used was manufactured by Mettler Toledo and equipped with a 1 L glass medium-pressure reactor and automatic feeding device.¹¹ The RC1e was used to study the synthesis rate and exothermic feature of the reaction. All of the RC1e experiments were carried out in the isothermal mode.

2.2.2. Differential Scanning Calorimetry. Differential scanning calorimetry (DSC) is a widely used thermal analysis tool to study the thermal stability of hazardous chemicals.^{12–14} In this work, the thermal stability of the final reaction mixture was quantitatively tested by DSC in the dynamic mode. The differential scanning calorimeter used was manufactured by Mettler Toledo. The samples were sealed in gold high-pressure crucibles (30 μ L) with gold-plated pads. The sample masses were about 1.2 mg. All of the DSC tests were conducted under a N₂ atmosphere.

2.2.3. Fourier Transform Infrared Spectrometry and ¹H Nuclear Magnetic Resonance Spectroscopy. FTIR and ¹H NMR were employed to check whether the desirable DINA was formed. The IR spectra were recorded in KBr using a Nicolet iS10 FTIR spectrometer. ¹H NMR spectra were obtained using a Bruker Avance III 500 MHz spectrometer. The chemical shifts (δ) are reported in parts per million downfield from tetramethylsilane as an internal standard. To conduct the ¹H NMR analyses, the products obtained from RC1e experiments were dissolved in dimethyl sulfoxide (DMSO) as the solvent.

2.2.4. High-Performance Liquid Chromatography. HPLC was used to quantitatively determine the yields of the products from RC1e experiments. The HPLC apparatus was manufactured by Waters. The solvent system was acetonitrile/water (70:30) at a flow rate of 0.8 mL/min with UV detection at 210–400 nm. The HPLC result for the standard sample of DINA is shown in Figure S1.

2.3. Synthesis of DINA. All of the DINA synthesis reactions were carried out in the RC1e. All of the experiment runs were carried out in the isothermal mode. The typical synthesis procedure for DINA is as follows: first, acetic anhydride with a small amount of fuming nitric acid (mass ratio of acetic anhydride to fuming nitric acid \approx 7:1) was added into the reactor; then diethanolamine hydrochloride and fuming nitric acid were simultaneously dosed into the reactor from two different streams after the reaction mixtures had reached the set temperature. After the dosing process, the temperature of the reaction system was slowly raised to 40 °C at constant rise rate of about 1 °C/min. The whole heat flow profiles for runs 2 and 3 are shown in Figures S2 and S3. It was experimentally found that the heat generation rate within and

after the temperature rising process presented significant oscillation. The heat released within and after the temperature rising process is close to zero and consequently can be neglected. After the reactions, the reaction mixtures were poured onto ice to crystallize the desirable DINA. The crystallized DINA was washed with deionized water and then filtered in vacuum. Finally, the DINA obtained was dried at 40 $^{\circ}$ C for 8 h.

To optimize the DINA synthesis conditions from both the safety and productivity points of view, three RC1e tests were conducted. The specific operating conditions of the three RC1e tests are listed in Table 1. For runs 2 and 3, the masses

 Table 1. Reaction Conditions for the Three RC1e

 Experiments

run	DEAHC:HNO3:Ac2O molar ratio	reaction temperature (°C)
1	1:4.5:4.8	10
2	1:4.5:6	10
3	1:4.5:6	5

of initially added acetic anhydride and fuming nitric acid were 350 and 50 g, respectively. During the dosing period, 80 g of diethanolamine hydrochloride and 160 g of fuming nitric acid were simultaneously added into the reactors.

The DINA yield was calculated using the following formula:

DINA yield =
$$\frac{n(\text{DINA})}{n(\text{DEAHC})} \times 100\%$$
 (1)

where n is the molar amount.

3. RESULTS AND DISCUSSION

3.1. Synthesis and Characterization. *3.1.1. Optimization of the Acetic Anhydride Content.* Since acetic anhydride acts as both the solvent and dehydrating agent in the synthesis of DINA, the mole fraction of acetic anhydride in the reaction mixture should play an important role. To study the effect of acetic anhydride, runs 1 and 2 were carried out. The heat flow profiles obtained from these RC1e experiments are shown in Figures 1 and 2, respectively. The heat production rates within the dosing period for both runs 1 and 2 are relatively stable. Once the addition of DEAHC stops, the heat production rates rapidly decrease to zero. These results indicate that the



Figure 1. Heat flow and dosing profiles for run 1.



Figure 2. Heat flow and dosing profiles for run 2.

reaction rates for both runs 1 and 2 are high and dosingcontrolled, which means that the reaction can rapidly stop once the additions of both fuming nitric acid and DEAHC stop, which is desirable from the thermal safety point of view.

It is worthwhile to note that the heat flow profile for run 1 shows a sharp exothermic peak just after the dosing period, which is attributed to the crystallization phenomenon in the reactor. The crystallization phenomenon is evidenced by the picture in Figure 1, which illustrates the mass mixture in the reactor. The RC1e test was manually stopped after the appearance of crystallization. HPLC and ¹H NMR analyses, as shown in Figures S4 and S5, proved that the white precipitate in the reactor is mainly composed of DINA. The crystallization phenomenon indicates that DINA is supersaturated in the reaction mixture of run 1. From the thermal safety point of view, the crystallization phenomenon is undesirable because hot spots may occur in the reactor. According to eq 1, the yield of DINA for run 1 was calculated to be about 75%.

To restrain the crystallization phenomenon, a greater amount of acetic anhydride was used for the RC1e test. We found that when the Ac₂O:DEAHC molar ratio was increased from 4.8:1 to 6:1, the crystallization phenomenon did not occur at all. This was evidenced by the fact that no exothermic peak appeared after the dosing period in Figure 2. The reaction mixture of run 2 in the reactor remained clear over the whole reaction. Moreover, the product obtained from run 2 was analyzed by HPLC and ¹H NMR, as shown in Figures S6 and S7. The chemical shifts at δ 4.15 and δ 4.74 correspond to hydrogen atoms on the methylene groups of DINA. The HPLC result indicated that the purity of DINA obtained from run 2 was higher than 99%. The DINA yield for run 2 was calculated to be 82%, which is higher than that for run 1.

From the above results, one can conclude that increasing the $Ac_2O:DEAHC$ molar ratio of from 4.8:1 to 6:1 can significantly improve the synthesis of DINA from both the safety and productivity points of view. However, as shown in Table S1, the yield of DINA increased just by about 1% when the $Ac_2O:DEAHC$ molar ratio was further increased to 8:1. Hence, increasing the amount of acetic anhydride further is not necessary.

3.1.2. Optimization of the Reaction Temperature. To study the effect of the reaction temperature on the synthesis of DINA, the reaction temperature was decreased from 10 to 5 $^{\circ}$ C. The heat flow profile for run 3 is shown in Figure 3. One



Figure 3. Heat flow and dosing profiles for run 3.

can see that the heat production rate was also stable over the whole reaction. Though the heat flow curve after the addition of DEAHC for run 3 does not decrease to zero as fast as that for run 2, the thermal accumulation for run 3 is still lower than 4%. This value of thermal accumulation will not lead to a thermal accident even if the cooling system fails to work, which will be explained in detail in the next section.

In addition, over the whole reaction for run 3, no crystallization phenomenon occurred, which means that the produced DINA was totally dissolved in the reaction mixture. The FTIR, ¹H NMR, HPLC, and ¹³C NMR results for the

product of run 3 are shown in Figures 4, 5, 6, and S8,



Figure 4. IR spectrum of the product of run 3.

respectively. The wavenumbers at 1675–1621 and 1515 cm⁻¹ in Figure 4 correspond to the characteristic peaks of O-NO₂ and N-NO₂. The chemical shifts at δ 4.2 and δ 4.8 correspond to the hydrogen atoms of the two types of methylene groups in DINA. The FTIR, ¹H NMR, and ¹³C NMR results indicate that DINA was formed. The HPLC result in Figure 6 indicates that the purity of the formed DINA was >99%. The yield of DINA for run 3 was determined to be about 92%, which is significantly higher than that for run 2. The increase in the yield of DINA indicates that decreasing the reaction temperature is favorable for the formation of DINA.



Figure 5. ¹H NMR spectrum of the product of run 3.



Figure 6. HPLC result of the product of run 3.

3.2. Thermal Risk Analysis. Since the yield of DINA for run 3 was the highest, thermal risk analysis was conducted only for run 3. The cooling failure scenario is generally considered as the most extreme situation for exothermic reactions that are carried out in semibatch reactors. To guarantee the thermally safe operation of the synthesis of DINA, the second decomposition reactions should be avoided in the case of cooling failure.

3.2.1. Maximum Temperature of the Synthesis Reaction. It is generally accepted that the maximum temperature of the synthesis reaction (MTSR) can be used to characterize the cooling failure scenario.¹⁵⁻¹⁷ The MTSR can be calculated as

$$MTSR = T_{p} + X_{ac,max} \Delta T_{ad}$$
⁽²⁾

where $T_{\rm p}$ is the process temperatue, $X_{\rm ac,max}$ is the maximum accumulation of the unreacted reactant, and $\Delta T_{\rm ad}$ is the adiabatic temperature rise of the exothermic reaction.

Through integration of the heat flow profile in Figure 3, the total heat generated in run 3 was found to be about 208.15 kJ. Accordingly, the reaction enthalpy $(-\Delta H_r)$ with respect to DEAHC was calculated to be about 368.9 kJ/mol. The corresponding value of $\Delta T_{\rm ad}$ for run 3 was calculated to be 152.84 K. In addition, the thermal conversion at the dosing end point was about 96.9%. Accordingly, the thermal accumulation for run 3 was equal to 3.1%. From these values, the MTSR for run 3 was determined to be 9.74 °C.

3.2.2. Thermal Risk of the Second Decomposition Reaction. For the synthesis of DINA, the accumulation of the unstable intermediate (i.e., DIA) is an important risk source. Combining the RC1e and HPLC results for run 3, one can reasonably expect that the DIA formed by O-nitration is rapidly converted to the final product DINA, indicating that the accumulation of DIA during the DINA synthesis process can be neglected. The thermal stability of the final reaction mixture of run 3 was tested by dynamic DSC experiments and characterized by the concept of time to maximum rate under adiabatic situation (TMR_{ad}).^{18–20} Figure 7 shows the heat flow



Figure 7. DSC test results for the final reaction mixture of run 3 at different heating rates.

profiles from the DSC tests. The operating conditions and results of the DSC tests are listed in Table 2. It can be seen that with an increase in the heating rate, the onset decomposition temperature (T_{onset}) of the final reaction mixture gradually increases.

Table 2. Operating Conditions and Results of DSC Tests forthe Final Reaction Mixture of Run 3

test no.	heating rate (°C/min)	sample mass (mg)	$\stackrel{T_{\text{onset}}}{(^{\circ}\text{C})}$	$-\Delta H_{\rm d}$ (J/g ⁻¹)
1	4	1.27	123.1	934.3
2	6	1.1	135.7	812.0
3	8	1.2	145.4	867.8

AKTS software was employed to calculate TMR_{ad}. The kinetic analysis was carried out using the Friedman approach, which is an isoconversional method. The basis of the isoconversional method is to determine the correspondence between the temperature and a certain reaction process value. The comparison between the experimental and simulated reaction progress profiles are shown in Figure 8. The correlation coefficient in Figure 8 is higher than 0.99, which proves the validation of the simulated results. The average decomposition heat $(-\Delta H_d)$ was determined to be 871.4 J/g.

Figure 9 shows the dependence of TMR_{ad} on the temperature as calculated using the AKTS software. One can see that when the value of TMR_{ad} is equal to 24 h, the corresponding temperature is 61.9 °C, that is, $T_{D24} = 61.9$ °C.

3.2.3. Risk Assessment. From the above results, one can see that the MTSR (9.74 °C) is significantly lower than T_{D24} (61.9



Figure 8. Comparison between the experimental and simulated reaction progress profiles.



Figure 9. TMR $_{\rm ad}$ vs temperature profile for the final reaction mixture of run 3.

°C). This implies that as the addition immediately stops in the case of a cooling failure, the decomposition of the formed DINA will not occur. This is desirable from the thermal safety point of view.

Since the synthesis of DINA is strongly exothermic, the temperature of the reaction mixture may deviate from the allowable range if the dosing rates of fuming nitric acid and DEAHC are accidently higher than the designed values. One can reasonably expect that if about 40% of the dosed reactants are accidently added into the reactor in a short time, the temperature will increase up to 66.1 °C, which is higher than T_{D24} , and consequently, the second decomposition reaction will be triggered. Therefore, the dosing rate of fuming nitric acid and DEAHC must be limited by reliable technical treatment.

With respect to the HNO₃/MgO nitration system, the reaction mixture becomes sticky during the reaction process as a result of the formation of suspended $Mg(OH)_2$.⁶ This phenomenon is undesirable because hot spots may appear in the sticky reaction mixture. Since the reaction mixture for the synthesis route reported in this work is homogeneous and clear over the whole reaction process, hot spots are less possible to generate compared with the HNO₃/MgO nitration system.

4. CONCLUSION

The synthesis of DINA by nitration of DEAHC with the fuming nitric acid/acetic anhydride (HNO₃/Ac₂O) system has been reported in this article. The optimized reaction conditions are a DEAHC:HNO₃:Ac₂O molar ratio of 1:4.5:6 and a reaction temperature of 5 °C. The yield of DINA can reach ~92% under these optimized operating conditions.

In addition, a thermal risk analysis has been carried out for the optimal operating conditions. The value of $T_{\rm D24}$ for the final reaction mixture was calculated to be 61.9 °C, which is significantly higher than the value of the MTSR (9.74 °C). This result indicates that as long as the addition immediately stops in the case of the cooling failure scenario, decomposition of the formed DINA will not occur.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.oprd.9b00300.

RC1e experiment results; HPLC, ¹H NMR, and ¹³C NMR results; reaction conditions for the laboratory-scale experiments (PDF)

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Notes

The authors declare no competing financial interest.

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