

Increasing the Yield of 2-Nitrobenzaldehyde During Benzaldehyde Nitration by Mixed Acid: Chemical and Safety Investigation

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The 2-nitrobenzaldehyde is an important intermediate currently obtained through the nitration of benzaldehyde by means of mixed acid. Unfortunately this process is characterized by poor yield in the target product coupled to considerable risks in its management due to the intrinsic hazard of the nitrations reactions. In the present investigation the production of the target mononitroderivative is studied by a chemical and kinetic point of view. The present investigations aims to clarify the behavior of the system, mixed acid and benzaldehyde, at varying the operative conditions (temperature and chemical composition of the nitrating system) to increase the yield in the product of interest and, at the same time, to reduce the risks connected to the process.

1. Introduction

The nitro derivatives of benzaldehyde (Be) are useful starting materials in the synthesis of fine chemicals such as dyes, pesticides, drugs and non-linear optic materials (Wang et al, 1988). The large number of methods to obtain these compounds is completely explained by the importance of the applications proposed. Actually the most important isomer, the ortho-mononitro (2NB), is difficult to obtain in good yield and high purity (Sainz-Diaz et al,1999). The classical method to obtain the mononitro-benzaldehydes through the nitration of benzaldehyde by means of the mixed acid, yields mainly 3-nitrobenzaldehyde (3NB) (Davey et al,1950) with considerable risks in the management of the process. In fact, it is well known that, since the nitrations are exothermic reactions, runaway phenomena can occur during processes as the result of polynitration and side reactions which take place when the thermal control of the process is lost (Andreozzi et al, 2005, Maestri et al, 2009). On the basis of these considerations, the behaviour of the target system, benzaldehyde and mixed acid, has been study to investigate how to increase the yield of the product of interest (ortho-mononitro). Isothermal experiments have been carried out varying both the temperature and the composition of the nitrating mixture to assess the influence of these variables on the process. It is well known that, to correctly describe the kinetic law regulating the reactions involved in nitration process, it is important to know the dependence of the protonating power of the medium (acidity function) on the temperature and on the composition of the mixed acid (Di Somma et al, 2012). In particular, the results obtained have shown that the yield in 2-nitrobenzaldehyde increases with the ratio HNO₃/H₂SO₄; unfortunately, at the same time, the hazards of the process increase, for which a safety characterization of the system was necessary. Therefore the present investigations attempted to clarify all these aspects.

2. Material and methods

The experiments has been performed in isothermal mode in a jacketed glass magnetically stirred (volume: $3.0 \cdot 10^{-2}$ L) reactor. 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 by charging in the reactor a previously formed and cooled solution of sulfuric acid, water and nitric acid to which the substrate has been then added. The concentration of the involved species as a function of reaction time has been recorded by submitting chemically quenched samples (with a dilution in acetonitrile), collected during the experiments, to HPLC analysis using a Hewlett-Packard model 1100 II, equipped with an UV-VIS detector and a Phenomenex Synergi 4μ polar RP/80A column. The following operating conditions have been adopted: the mobile phase has been formed by 25 % of a buffer solution (vol %: CH_3OH 5%, H_3PO_4 0.4%, H_2O 94.6%) and 65% of acetonitrile, the signals have been acquired at 210, 220, 230, 250, 275 nm, the column temperature has been kept at 298 K and the flow rate set at $1 \cdot 10^{-3}$ $\text{L} \cdot \text{min}^{-1}$. For all the experiments analytical grade 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 the thermal control is one of the most frequent and dangerous process deviations in chemical industry (Andreozzi et al, 2006) 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 (Di Somma et al, 2012). On the basis of these considerations, during a safety assessment for a chemical process, the behavior of the system at varying the operating conditions needs to be identified. In fact it is well known that both, the operating temperature and the protonating power of the medium, depending on the mixed acid composition and which can be measured by the acidity function H defined as:

$$H = -\log \frac{a_{\text{H}_2\text{SO}_4}}{a_{\text{H}_2\text{O}} \cdot a_{\text{HSO}_4^-}} \quad (1)$$

can influence the safety of the process. For these reasons preliminary experiments of nitration of benzaldehyde with mixed acid have been performed varying separately only one of these parameters. In other words some runs have been firstly performed at fixed initial concentrations of both, substrate and nitrating mixed, varying the temperature and successively, at temperature values (293K) already tested, the experiments have been repeated with different reactive mixture compositions. So the nitration of benzaldehyde (Be) has been investigated, under isothermal conditions, at different temperatures with a nitrating mixture composition fixed (%w/w: HNO_3 = 20 %, H_2O = 20 %, H_2SO_4 = 60 %). In general the data obtained indicate that the mononitration happens at ambient or near ambient temperature and that the reactivity of the system increases with the operating temperature (Figure 1).

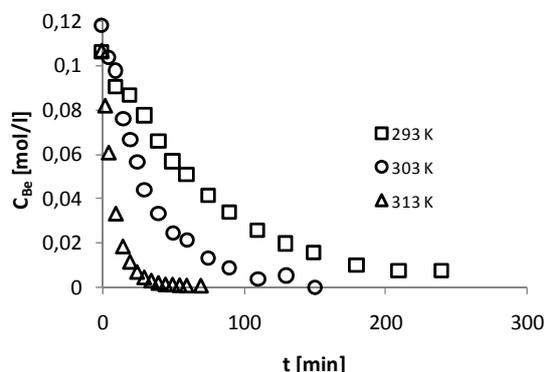


Figure 1: Benzaldehyde's consumption in nitrations performed at fixed mixed acid varying the temperature.

In Figure 2 the results obtained during one of these runs performed at 293 K are reported in terms of decay of the substrate and formation of the products. From these results it is possible to state that, for the

operating conditions adopted, the main product is 3-nitrobenzaldehyde (3NB), with a minor occurrence of 2-nitrobenzaldehyde (2NB) and of 4-nitrobenzaldehyde (4NB) at trace levels.

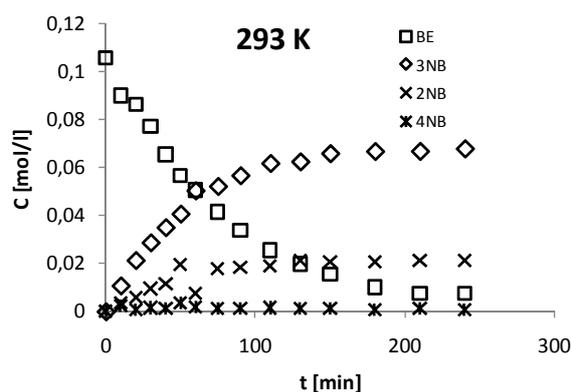


Figure 2: Nitration of benzaldehyde at 293 K.

It has been reported in the literature (Sainz-Diaz et al, 1999) that a higher portion of nitric acid could yield a slightly higher amount of ortho-mononitroderivative probably due to the capability of the aldehyde group to coordinate the NO_2^+ ion and so to promote the ortho-substitution. Some runs have been thus carried out at varying the mixed acid composition at a fixed temperature of 293 K.

In table 1 the operating conditions adopted during the investigations have been reported.

Table 1: Adopted operating conditions in the investigations

T [K]	C_{Be} [mol/L]	%HNO ₃ [w/w]	%H ₂ SO ₄ [w/w]	%H ₂ O [w/w]	Slope/($C_{\text{Be}}C_{\text{HNO}_3}$) [L/(mol min)]
293	0.116	14	60	26	$4.05 \cdot 10^{-5}$
293	0.116	16	60	24	$1.33 \cdot 10^{-4}$
293	0.120	17	60	23	$2.97 \cdot 10^{-4}$
293	0.120	20	60	20	$2.91 \cdot 10^{-3}$
293	0.117	23	57	20	$2.65 \cdot 10^{-3}$
293	0.130	22	59	19	$9.24 \cdot 10^{-3}$
293	0.120	20	63	17	$2.24 \cdot 10^{-2}$
293	0.126	23	60	17	$2.24 \cdot 10^{-2}$
293	0.126	21	63	16	$6.22 \cdot 10^{-2}$
293	0.126	25	60	15	$9.14 \cdot 10^{-2}$
293	0.123	26	60	14	$1.37 \cdot 10^{-1}$
293	0.176	29	59	12	$2.12 \cdot 10^{-1}$
293	0.212	33	67	0	(Not evaluable, too fast)

In Fig. 3 the yield of 2-nitrobenzaldehyde is reported for each run of this set.

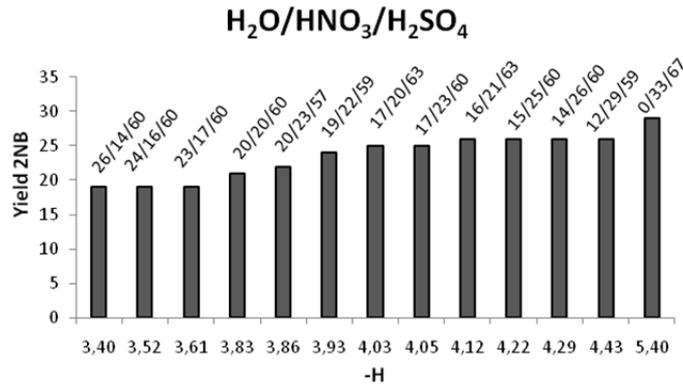


Figure 3: Yield of 2-nitrobenzaldehyde for each run reported in Table 1.

From the results reported in Figure 3 it is evident that the yield of 2-nitrobenzaldehyde in the target process increases (from 20 % to about 29 %) with nitric acid concentration.

Unfortunately it is well known that an increase in nitric acid concentration gives rise to an increase in the acidity function H (Di Somma et al, 2012):

$$-H = \left(0.56 \cdot C_{H_2SO_4} + 0.52 \cdot C_{HNO_3}\right) \cdot \left(0.33 + \frac{49.0}{T}\right) \quad (2)$$

which results into a higher reactivity.

In fact, an analysis of the data reported in sixth column of table 1 (calculated from the slope of the benzaldehyde decay in each run divided by nitric acid and substrate concentration) indicates that an increase of H influences significantly also the reactivity of the system. However, looking at the same values one can state that the yield does not increase monotonically at increasing nitric acid concentration and that an optimal mixed acid composition can be chosen to have a good yield for 2-nitrobenzaldehyde with a reactivity which is not the highest one.

Being nitrations exothermic reactions, an increase in the reactivity involves higher rate of heat production; so, the possibility of losing the thermal control of the process increases with the reaction rate (that is with H), resulting in an higher probability of occurrence of runaway phenomena due to polynitration and/or side reactions. In fact, assuming a heat of reaction equal to 1185 J/g for the nitration of the benzaldehyde, 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 mono-nitration of the substrate as:

$$\Delta T_{ad} = \frac{\Delta H_{nit}}{3 \cdot cp_M} = 197 K \quad (3)$$

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 dinitration reactions surely start (Olah et al, 1989). With a similar approach, if one considers that nitric acid is present in the reacting solution at a large excess with respect to benzaldehyde, the possibility can be demonstrated that a loss of thermal control can allow the formation of less thermally stable trinitroderivatives of the substrate (Cho et al, 2005).

Therefore, there is an interest to have the possibility of predicting the system reactivity starting from the mixed acid composition. A first attempt to do this has been done on the basis of the classic reaction mechanism known from the literature (Di Somma et al, 2012) for nitration, although the change in the selectivity for 2-nitrobenzaldehyde, observed in the present investigation at increasing nitric acid concentration, is not consistent with it.

The kinetic law that can be written in this case is the following (Di Somma et al, 2012):

$$\frac{dC_{Be}}{dt} = -k_N \cdot \frac{\gamma_{HNO_3 \cdot H_2O}}{\gamma_{H_2O}} \cdot 10^{-H} \cdot \frac{1}{C_{H_2O}} \cdot C_{HNO_3} \cdot C_{Be} \quad (4)$$

Adjusting this correlation to pointing out the relation between reactivity and H:

$$\frac{dC_{Be}}{dt} \cdot \frac{1}{C_{HNO_3} \cdot C_{Be}} = -k_N^* \cdot 10^{-H} \cdot \frac{1}{C_{H_2O}} \quad (5)$$

where the ratio of the activity coefficients have been assumed constant and then incorporated in k_N^* .

Taking the logarithms of both members of the (5) and approximating the initial time derivative with the finite difference it is possible to obtain:

$$\log\left(-\frac{\Delta C_{Be}}{\Delta t} \cdot \frac{1}{C_{HNO_3} \cdot C_{Be}}\right) = \log(k_N^*) - [H + \log(C_{H_2O})] \quad (6)$$

Renaming the argument of the logarithm at the first member of the (6) as K (experimental second-order kinetic constant) the following equation is obtained:

$$\log(K) = \log(k_N^*) - [H + \log(C_{H_2O})] \quad (7)$$

To verify the capability of the relationship (7) to explain the different reactivities recorded during the experimental campaign, for each run reported in Table 1, the values shown in sixth column have been used in the equation (6) to calculate the logarithm of K (see Figure 4):

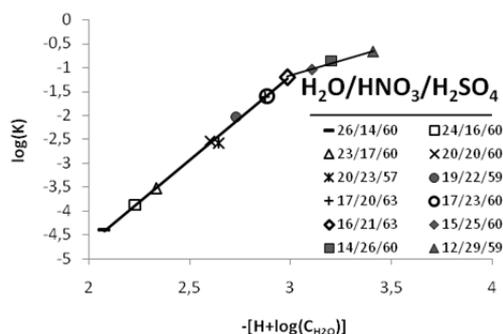


Figure 4: $\log(K)$ versus $[H+\log(C_{H_2O})]$ for each run reported in Table 1.

Two straight lines are observed, a first with a slope equal to about 1 for the highest values of the function $-[H+\log(C_{H_2O})]$, the second for the remaining points with a higher slope. For the values of the function $-[H+\log(C_{H_2O})]$, giving rise to this second straight line an increase of 2-nitrobenzaldehyde was observed. On the other hand, when the dependence of the logarithm of the real nitration kinetic constant upon $-[H+\log(C_{H_2O})]$ is given by the equation (7), no significant changes in the product selectivity were recorded. According to some literature findings, the occurrence of a change of the positional selectivity following a variation of the nitration medium can be ascribed to some interactions of the substrate with the latter (protonation, formation of complexes). In the case of benzaldehyde, it has been reported (Sainz-Diaz, 2002) the possibility of a coordination of nitronium ion with the substrate which can favour the formation of ortho isomer.

Moreover from Figure 4 it is possible to observe that the data related to the run performed in absence of water have not been reported; in fact, in this case the reactivity is so high that around the time zero the substrate concentration in the reactive mixture is practically nil.

4. Conclusions

The behavior of the system benzaldehyde/mixed acid has been studied to pointed out the dependence of the reactivity on both the temperature and the nitrating mixture composition. The present investigations indicates that the behavior of the system in terms of yield in the product of interest (2-nitrobenzaldehyde) and, at the same time, of global risks connected to the process depend on the nitric acid concentration in mixed acid. It has been shown that satisfactory values of this yield can be obtained with nitrating mixture compositions more safe than those reported in the literature.

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