

# Kinetics of Liquid-Phase Catalytic Hydrogenation of 4-Chloro-2-nitrophenol

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## Abstract:

Process parameters were studied to increase the selectivity of the haloamino compound by preventing the formation of dehalogenated product for the selective hydrogenation of 4-chloro-2-nitrophenol on 5% Pd/C catalyst. At a conversion ratio of 87%, 96% selectivity was achieved in 5 h. Kinetic interpretations have been made for this liquid-phase hydrogenation reaction.

## Introduction

The synthesis of 2-amino-4-chlorophenol has considerable industrial importance. It is mainly used as an intermediate for a drug, namely chlorzoxazone, which has been extensively used as a skeletal muscle relaxant.<sup>1</sup> It is also an intermediate for a large class of diazo components used for hydroxy azo dyes,<sup>2</sup> which are important for wool and polyamides when converted to their chromium complexes.

The main route for the synthesis of haloamino compounds is either the Bechamp's reaction or catalytic hydrogenation starting with halonitro aromatic compounds. The main drawback of Bechamp's reaction<sup>3</sup> is that the rate of reaction is lower than that of the catalytic hydrogenation due to lower solubility of the halonitro compounds in an acid-water system. Though the selectivity to the desired product is higher in Bechamp's process, the separation of the product from the reaction mixtures needs costly steam distillation. The catalytic hydrogenation of halonitro compounds using heterogeneous catalyst offers several advantages over chemical reduction. Some of the major ones are the following: (1) The cost of hydrogen is low compared to that of most other reducing agents. (2) The products can be easily separated at the end of the reaction, and loss of product during recovery is minimal. (3) The catalyst can be reused. (4) The process is environmentally friendly and nonpolluting. While the hydrogenation of nitro compounds, in general, is highly attractive, the extension of the process to halo-substituted nitroaromatic compounds poses several problems because there is a tendency towards hydrodehalogenation. It may be mentioned that the amino group in the desired product facilitates the hydrodehalogenation,<sup>4–7</sup> and therefore, the

tendency for its formation needs to be reduced, by choice of the proper reaction conditions, the type of catalyst, and the solvent.

The information available regarding this processes is inadequate and is mostly confined to the patent literature. Hence, the present work was undertaken to ascertain the suitable process conditions and kinetics for the manufacture of the desired product, 2-amino-4-chlorophenol.

## Experimental Section

**Experimental Setup.** Experiments were carried out in an autoclave of 100 mL capacity, made of Hastelloy. The autoclave was equipped with a four-bladed magnetically driven impeller, and a cooling system was arranged in it. The autoclave was heated externally by a heating element, and the temperature of the reaction was regulated by a temperature indicator controller. The pressure gauge, pressure release valve, safety head port, and sampling valve were all situated on the top head.

**Experimental Procedure.** Predetermined quantities of 4-chloro-2-nitrophenol, methanol, and catalyst were charged to the autoclave, and the autoclave was repeatedly purged first with nitrogen and then with hydrogen gas. The reaction temperature was maintained within  $\pm 1$  °C of the desired level by controlling the flow rate of cooling water and the heating rate. The autoclave was pressurized with hydrogen to the desired pressure and agitation started. The reaction time was noted from this instant. A constant pressure was maintained throughout the reaction period.

**Analysis.** Samples of 1–2 mL, withdrawn at regular intervals of time, were analyzed by gas chromatography on a Chemito 8510 instrument equipped with a flame ionization detector, connected to an integrator. A 2-m-long, 0.003-m-diameter stainless steel column with 10% SE-30 on Chromosorb-W was used. The injector and detector temperatures were maintained at 300 °C, and the oven temperature was maintained at 150 °C isothermally. The carrier gas used was nitrogen with a flow rate of 20 mL/min.

**Separation and Purification of the Product.** The reaction mixture taken out from the autoclave was filtered to remove the catalyst, and then methanol was distilled out under reduced pressure. The product mixture was acidified (pH = 3–4) with 20% hydrochloric acid. This solution was then neutralized with concentrated sodium hydroxide to obtain a precipitate at pH 6–7. This precipitate was filtered

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(1) Wang, S.; Xiangbin, Y.; Deyu, X. *Yiyao Gongye* 1987, 18 (2), 49–50 (Chinese); *Chem. Abstr.* 1987, 107, 198147.

(2) *Ullmann's Encyclopedia of Industrial Chemistry*, 5th ed.; VCH: Weinheim, 1985; Vol. A17, p 447.

(3) *Ullmann's Encyclopedia of Industrial Chemistry*, 5th ed.; VCH: Weinheim, 1985; Vol. A2, p 43.

(4) Stratz, A. M. *Catalysis in Organic Reactions*; Marcel Dekker: New York, 1994; p 353.

(5) Freifelder, M.; Martin, W. B.; Stone, G. R.; Coffin, E. L. *J. Org. Chem.* 1961, 26, 383.

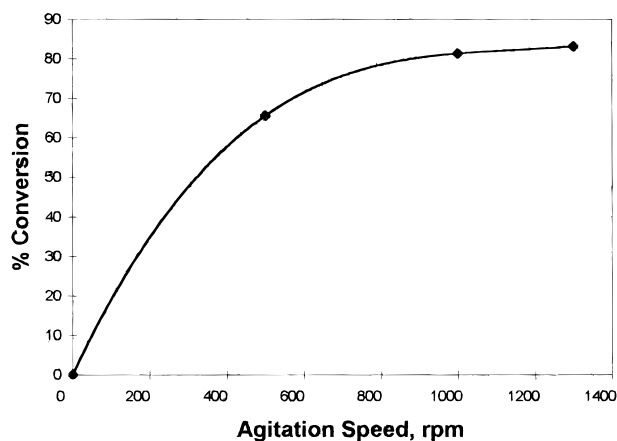
(6) Kindler, K.; Oelschlager, H.; Henrich, P. *Chem. Ber.* 1953, 86, 167.

(7) Kindler, K.; Oelschlager, H.; Henrich, P. *Chem. Ber.* 1953, 86, 501.

**Table 1. Material balance<sup>a</sup>**

| material               | gmol    | % accounted for |
|------------------------|---------|-----------------|
| 4-chloro-2-nitrophenol | 0.0288  | 100             |
| 2-amino-4-chlorophenol | 0.02361 | 82              |
| dehalogenated product  | 0.00057 | 2               |
| unreacted              | 0.00369 | 12.8            |
| unaccounted for        | 0.00093 | 3.2             |

<sup>a</sup>Reactions conditions: 4-chloro-2-nitrophenol, 10% w/v; catalyst, palladium on carbon; catalyst loading, 3.0 g/L; reaction time, 5 h; temperature, 100 °C; speed of agitation, 1000 rpm; hydrogen pressure, 25 atm; volume of reaction mixture, 50 mL; reactant taken, 0.0288 gmol; total accounted for, 0.02787 gmol; material accounted for, 97%.



**Figure 1.** Effect of speed of agitation. Reaction conditions: initial concentration of reactant, 10% w/v; catalyst loading, 3 g/L; temperature, 100 °C; time, 5 h; hydrogen pressure, 25 atm; reaction volume, 50 mL.

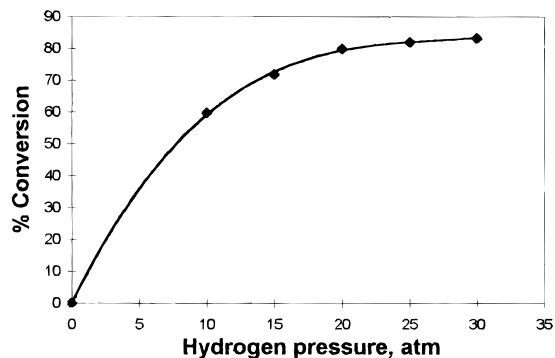
and washed with water three times to get the pure desired product

## Results and Discussion

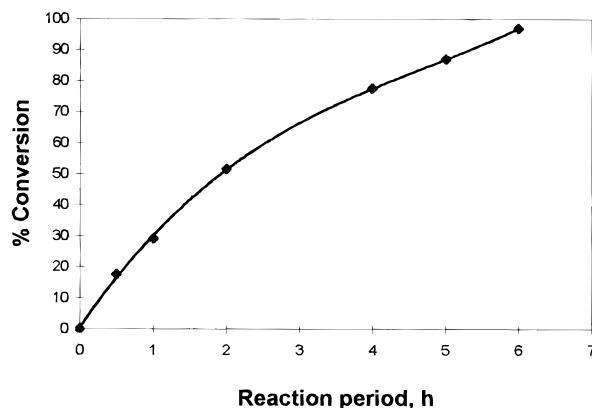
**Material Balance.** During this hydrogenation reaction of 4-chloro-2-nitrophenol, 97% 4-chloro-2-nitrophenol could be accounted for on an isolation basis (Table 1).

**Effect of Speed of Agitation.** To ascertain that mass transfer plays an insignificant role, speed of agitation was varied from 500 to 1200 rpm in this hydrogenation reaction. There was a significant change in the overall conversion when the agitation speed was varied from 500 to 1000 rpm, indicating the presence of the mass-transfer limitation for the diffusion of hydrogen from the gas interface to the bulk liquid. When the speed of agitation was further increased from 1000 to 1200 rpm, there was no significant change in the overall conversion (Figure 1). This indicates that mass-transfer effects are mostly eliminated at or above 1000 rpm and that the data represent the true kinetics of the process.

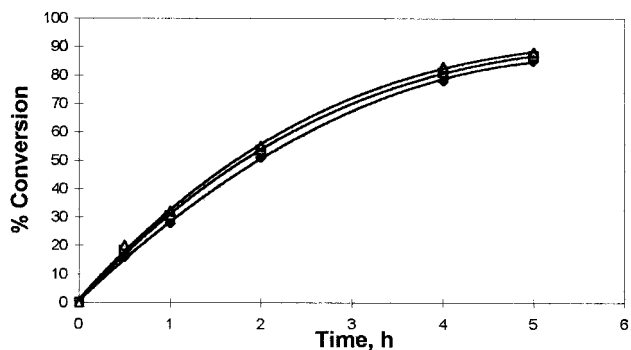
**Effect of Partial Pressure.** When the pressure was increased from 10 to 25 atm, it was observed that the percent overall conversion observed after 5 h reaction increased markedly (Figure 2). However, with a further increase in the pressure from 25 to 30 atm, there was no significant increase in conversion observed after 5 h of reaction. Thus, under hydrogen-rich conditions, the reaction is independent of the partial pressure of hydrogen. All subsequent reactions were done at a pressure of 25 atm.



**Figure 2.** Effect of hydrogen pressure. Reaction conditions: initial concentration of reactant, 10% w/v; catalyst loading, 3 g/L; temperature, 100 °C; speed of agitation, 1000 rpm; time, 5 h; reaction volume, 50 mL.



**Figure 3.** Effect of period of reaction. Reaction conditions: initial concentration of reactant, 10% w/v; catalyst loading, 3 g/L; temperature, 100 °C; speed of agitation, 1000 rpm.

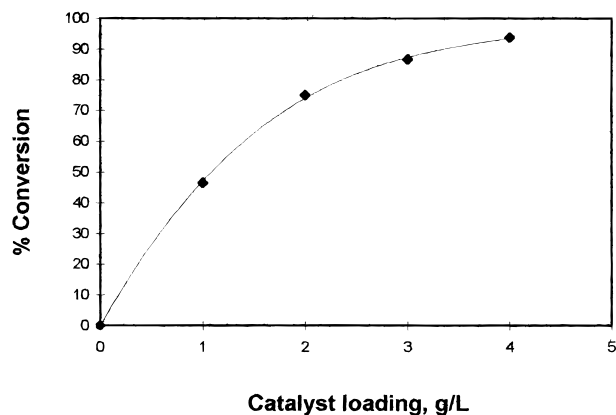


**Figure 4.** Effect of initial concentration. Reaction conditions: hydrogen pressure, 25 atm; catalyst loading, 3 g/L; temperature, 100 °C; speed of agitation, 1000 rpm; time, 5 h; reaction volume, 50 mL. Symbols (% w/v): ◆, 5; □, 10; △, 20.

**Effect of Period of Reaction and Initial Concentration.** When the period of reaction was increased from 0.5 to 5 h, the overall conversion of 4-chloro-2-nitrophenol under 25 atm hydrogen pressure increased from 18 to 87%, and the selectivity with respect to the amino phenol was 96% (Figure 3).

It is observed from Figure 4 that there was a little increase in the percent overall conversion as the concentration increased from 5 to 20% (w/v).

**Effect of Catalyst Loading and Reusability of the Catalyst.** The catalyst loading, expressed as weight percent



**Figure 5.** Catalyst loading vs % overall conversion. Reaction conditions: hydrogen pressure, 25 atm; initial concentration, 10% w/v; temperature, 100 °C; speed of agitation, 1000 rpm; time, 5 h; reaction volume, 50 mL.

**Table 2.** Effect of reusability of catalyst<sup>a</sup>

| catalyst     | conversion of CNP, % | selectivity with respect to ACP, % |
|--------------|----------------------|------------------------------------|
| fresh        | 86.7                 | 97.6                               |
| first reuse  | 84.7                 | 97.1                               |
| second reuse | 83.9                 | 96.3                               |

<sup>a</sup>Reactions conditions: 4-chloro-2-nitrophenol, 10% w/v; catalyst, palladium on carbon; catalyst loading, 3.0 g/L; reaction period, 5 h; temperature, 100 °C; speed of agitation, 1000 rpm; hydrogen pressure, 25 atm; volume of reaction mixture, 50 mL. CNP, 4-chloro-2-nitrophenol; ACP, 2-amino-4-chlorophenol.

**Table 3.** Effect of different types of catalysts<sup>a</sup>

| catalyst loading | conversion of CNP, % | selectivity with respect to ACP, % |
|------------------|----------------------|------------------------------------|
| 5% Pd/C          | 87                   | 96                                 |
| Raney Ni type-I  | 84                   | 93                                 |
| Raney Ni type-II | 86                   | 9a                                 |

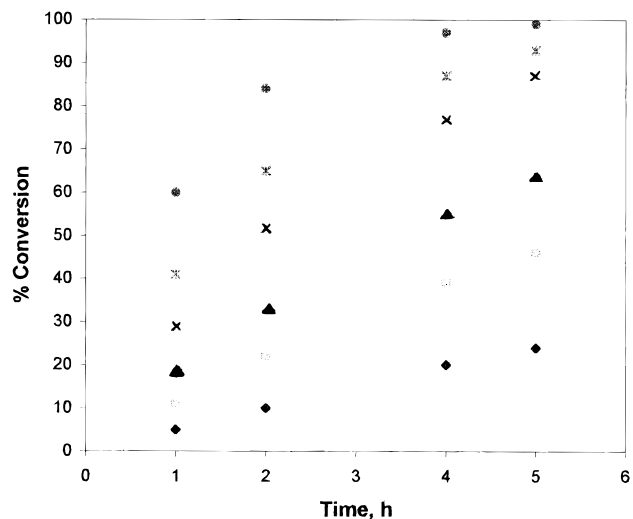
<sup>a</sup>Synthesis of 2-amino-4-chlorophenol from 4-chloro-2-nitrophenol. Reaction conditions: 4-chloro-2-nitrophenol, 10 w/v; speed of agitation, 1000 rpm; catalyst loading, 3.0 g/L; reaction period, 5 h; temperature, 100 °C; hydrogen pressure, 25 atm; volume of reaction mixture, 50 mL.

of catalyst based on the total reaction volume, was varied from 0.1 to 0.4% w/v (Figure 5). The percent overall conversion with respect to the reactant observed after 5 h of reaction time increased significantly.

It was observed (Table 2) that the activity as well as the selectivity was sustained for repeated uses of the catalyst.

**Effect of Different Types of Catalyst.** Different types of catalyst, such as 5% Pd/C, Raney Ni type-I, and Raney Ni type-II, were used for this reaction. Type-I and type-II differ in mesh size only. Though Raney Ni is a less expensive catalyst than 5% Pd/C, the selectivity obtained was lower, and the catalyst activity for repeated use was not sustained, so it was worth considering use of 5% Pd/C as the catalyst (Table 3).

**Effect of Temperature.** The effect of temperature was studied from 60 to 120 °C. The conversion of 4-chloro-2-nitrophenol increased from 24.34 to 100% when the temperature was increased from 60 to 120 °C (Figure 6). The selectivity decreased with respect to the desired product



**Figure 6.** Effect of temperature on rate of reaction. Reaction conditions: initial concentration of reactant, 10% w/v; catalyst loading, 3 g/L; speed of agitation, 1000 rpm; reaction period, 5 h; reaction volume, 50 mL. Symbols (°C): ◆, 60; ■, 80; ▲, 90; ×, 100; \*, 110; ●, 120.

**Table 4.** Effect of different solvents<sup>a</sup>

| solvent               | conversion of CNP, % | selectivity with respect to ACP, % |
|-----------------------|----------------------|------------------------------------|
| methanol              | 87                   | 96                                 |
| 2-propanol            | 84                   | 95                                 |
| aqueous NaOH solution | 32                   | 99                                 |

<sup>a</sup>Reaction conditions: 4-chloro-2-nitrophenol, 10% w/v; catalyst, palladium on carbon; catalyst loading, 3.0 g/L; reaction period, 5 h; temperature, 100 °C; speed of agitation, 1000 rpm; hydrogen pressure, 25 atm; volume of reaction mixture, 50 mL.

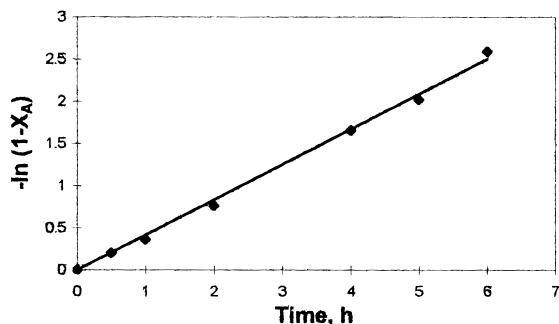
**Table 5.** Comparison of the rate of hydrogenation between Bechamp's process and the catalytic process

| process                 | reaction time, h | conversion, % |
|-------------------------|------------------|---------------|
| Bechamp's process       | 5                | 87            |
| catalytic hydrogenation | 5                | 67            |

from 96 to 89%, due to the faster rate of the hydrodehalogenation reaction at higher temperatures. Therefore, it was thought desirable to use a temperature of 100 °C to obtain a higher selectivity with respect to the desired product.

**Effect of Solvent.** Different types of solvents, such as methanol, 2-propanol, and aqueous sodium hydroxide solution, were used for this reaction. Methanol was proved to be the best solvent under the reaction conditions (Table 4). In alkaline conditions, though, the selectivity was as high as 99%, but the specific reaction rate was too slow. At 5 h, 32% conversion and 99% selectivity were obtained in alkaline solution.

**Comparison of the Rate of Reaction of This Process with Bechamp's Process.** In a view to compare the rate of reaction between the two processes, the reduction was performed with Fe/HCl as well as by hydrogenation on 5% Pd/C catalyst. It was found that (Table 5) the rate of reaction of Bechamp's process for 4-chloro-2-nitrophenol was lower than that of the catalytic process under similar reaction



**Figure 7.** Time vs  $-\ln(1 - X_A)$ . Reaction conditions: initial concentration of reactant, 10% w/v; catalyst loading, 3 g/L; temperature, 100 °C; speed of agitation, 1000 rpm; hydrogen pressure, 25 atm; reaction period, 5 h; reaction volume, 50 mL.

**Table 6.** Effect of initial concentration of nitro compound on specific rate constant<sup>a</sup>

| initial concn of nitro compound, % w/v | specific rate constant $\times 10^4$ , s <sup>-1</sup> |
|--|--|
| 5                                      | 1.05   |
| 10                                     | 1.13   |
| 20                                     | 1.22   |

<sup>a</sup> Reaction conditions: catalyst, palladium on carbon; catalyst loading, 3.0 g/L; reaction time, 5 h; temperature, 100 °C; speed of agitation, 1000 rpm; hydrogen pressure, 25 atm; volume of reaction mixture, 50 mL.

conditions. In 5 h, only 72% conversion was obtained in Fe/HCl reduction, in comparison to 87% in the catalytic hydrogenation. The selectivity in Bechamp's process was found to be 99%, which can also be achieved in catalytic hydrogenation by controlling the conversion to a lower ratio.

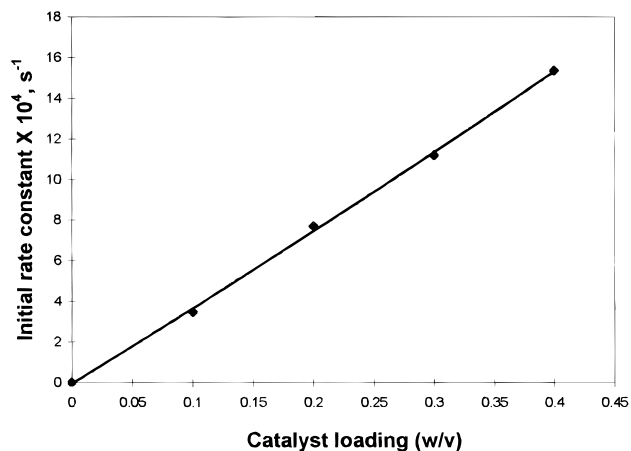
The Bechamp reaction was carried out at 75 °C, and after the stipulated period of time, the reaction mixture was hot filtered to remove iron metal and then neutralized with NaOH solution. The organic compounds were extracted in toluene and then fractionated using a 2-m wire mess pack column to isolate the product.

**Kinetic Interpretation.** The reactions were carried out at a high speed of agitation to eliminate the mass-transfer effects. There was absolutely no increase in the conversion ratio when the hydrogen pressure was increased from 10 atm. This indicates that, at or above 25 atm pressure, the reaction is insensitive to a further increase in pressure.

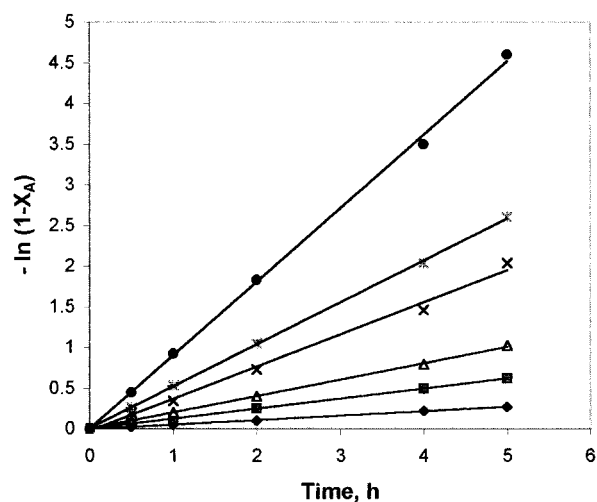
It is seen from Figure 7 and Table 6 that the reaction is a first-order reaction with respect to the chloronitrophenol at a hydrogen pressure of 25 atm, speed of agitation of 1000 rpm, and catalyst loading of 0.3% w/v.

It is observed that the initial rate increases linearly with the increase in catalyst loading (Figure 8). Since the catalyst used was finely powdered and micrometer-scale in size, the role of diffusion of hydrogen from the bulk liquid to the solid is estimated to be unimportant, and the data appear to represent the true kinetics of the process at a catalyst loading of 0.3% w/v.

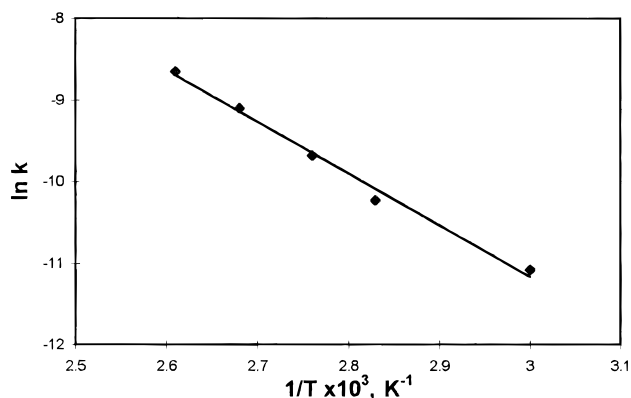
At different temperatures,  $-\ln(1 - X_A)$  vs  $t$  is plotted (Figure 9), and from the slopes,  $k$  values at different temperatures are found to be  $1.53 \times 10^{-5}$ ,  $3.43 \times 10^{-5}$ ,  $5.6 \times 10^{-5}$ ,  $1.1 \times 10^{-4}$ ,  $1.43 \times 10^{-4}$ , and  $2.5 \times 10^{-4}$  s<sup>-1</sup> under



**Figure 8.** Effect of catalyst loading on rate of reaction. Reaction conditions: initial concentration of reactant, 10% w/v; hydrogen pressure, 25 atm; temperature, 100 °C; speed of agitation, 1000 rpm; reaction volume, 50 mL; time, 5 h.



**Figure 9.**  $-\ln(1 - X_A)$  vs  $t$  at different temperatures. Reaction conditions: initial concentration of reactant, 10% w/v; catalyst loading, 3 g/L; hydrogen pressure, 25 atm; speed of agitation, 1000 rpm; reaction volume, 50 mL. Symbols (°C):  $\blacklozenge$ , 60;  $\blacksquare$ , 80;  $\blacktriangle$ , 90;  $\times$ , 100;  $*$ , 110.



**Figure 10.** Arrhenius plot. Reaction conditions: initial concentration of reactant, 10% w/v; catalyst loading, 3 g/L; hydrogen pressure, 25 atm; speed of agitation, 1000 rpm; reaction volume, 50 mL; time, 5 h.

the reaction conditions. The energy of activation is found to be 12.6 kcal/mol (Figure 10).

## Conclusion

It was observed that 0.3% w/v of 5% Pd/C was suitable for the hydrogenation of 4-chloro-2-nitrophenol under the reactions conditions. A temperature of 100 °C and a pressure of 25 atm were found to be most suitable for this reaction in methanol under the given conditions. The catalyst sustains its activity for subsequent uses.

The mass-transfer effects were eliminated at a speed of agitation of 1000 rpm at 100 °C and 25 atm hydrogen

pressure. The hydrogenation reaction follows a first-order kinetics with respect to nitro compound.

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