STUDIA UNIVERSITATIS BABEŞ-BOLYAI, CHEMIA, L, 1, 2005

MASS TRANSFER RATES DURING THREE PHASE CATALYTIC REDUCTIVE AMINATION OVER SUPPORTED NOBLE METALS

J. BÓDIS[1], L. BÓDIS[2] and J. A. LERCHER[3]

[1] "Babes-Bolyai" University, Department of Organic Chemistry, str. Arany Janos nr. 11,
400028 Cluj, Romania. E-mail: jbodis@chem.ubbcluj.ro. Fax: 40-264-190818
[2] Swiss Federal Institute of Technology Zürich, ETH Hönggerberg, HCI E 312,
CH-8093 Zürich, Switzerland
[3] Institut für Technische Chemie, Technische Universität München,
Lichtenbergstrasse 4, D-85747, Garching bei München, Germany

ABSTRACT. Reductive amination of butanal and methyl ethyl ketone (MEK) with ammonia (at ammonia/MEK molar ratios of ~ 14.5) and hydrogen has been performed at 50 bar and 323-353 K over graphite and charcoal supported noble metal catalysts. Rhodium and platinum based catalysts showed the highest activity in reductive amination of butanal and MEK. The rhodium catalysts had high selectivity towards primary amines while the platinum catalysts towards secondary amines. Tertiary amines were detected only in the reaction products resulted from butanal. The BET area and metal dispersion were found to have a pronounced influence on activity and selectivity. By varying the speed of stirring it was found that the mass transfer of hydrogen from the gas phase into the liquid did not limit the rate of reactions. Model calculations showed that mass transfer limitations of hydrogen diffusion from the liquid to the solid did not also influence the measured reaction rates.

Keywords: Reductive amination, Butanal, Methyl ethyl ketone, Noble metal catalysts, Mass transfer

INTRODUCTION

The reductive amination of aldehydes and ketones is an important synthetic route to amines. The reaction proceeds through an intermediately formed imine, hydrogenated with the help of a reducing agent or with molecular hydrogen in the presence of a catalyst. [1-3]. The resulting amines or imines are of great importance for the chemical and pharmaceutical industry. While the new amines are potential drug candidates, the pharmaceutical companies have a serious deficit concerning their amine libraries [4].

Butanal and methyl ethyl ketone were chosen as test molecules because of lack of literature information concerning the three phase catalytic reductive amination of these substrates with ammonia and hydrogen over supported noble metal catalysts [1-3]. In order to verify whether mass transfer limitations occur or not, experiments and mass transfer calculations were done [5].

EXPERIMENTAL

CATALYSTS: The catalysts tested in the reductive amination of butanal and methyl ethyl ketone (MEK) are presented in Table 1 together with some physicochemical characterization data as well. The charcoal supported catalysts contained 55-60% moisture. The quantitative values used for these samples refer to dry material.

Table 1

Catalysts characterization data (metal dispersions were calculated by using n_S values estimated according to literature [6]).

Type of catalyst	**S_{sp} (m^2/g)**	**S_M (m^2/g)**	**Metal location**	**Dispersion (%)**	**BET area (m^2/g)**
5%Rh/charcoal	950	11.1	Intermediate	50.43	817.8
5%Rh/HSAgraphite	130	9.5	Surface	43.17	94.6
5%Ru/HSAgraphite.	130	8.0	Surface	43.78	41.6
5%Pd/HSAgraphite	130	11.4	Surface	51.10	87.6
5%Pt/HSAgraphite	130	5.0	Surface	40.48	80.1
5%Pt/LSAgraphite	n.a.	3.5	Surface	28.0	56.7

S_{sp}	specific surface area of the support
S_M	metal surface area determined by hydrogen chemisorption
HSA	high surface area
LSA	low surface area

CATALYSTS TESTING: The reactions were carried out in batch reactors with a volume of about 65 ml. Magnetic stirring at a speed of 1100 rpm was used. The temperature inside the autoclave was measured by a thermocouple mounted on the lid of the autoclave. Weighed amount of catalysts were introduced into the autoclave. In order to assure a well-defined starting time for every reaction, the following experimental procedure was applied:

After addition of carbonyl compound (MEK or butanal) and of the solvent (ethanol), the autoclave was flushed with nitrogen to remove the atmospheric oxygen. Ammonia was then added from the liquid ammonia cylinder at room temperature. Then the autoclave was placed in a thermostat bath preset to the reaction temperature. The addition of hydrogen and the rapid completion to the working pressure occurred only after the preformed imine solution reached the desired reaction temperature (t = 0 is set for the time when the final pressure was established).

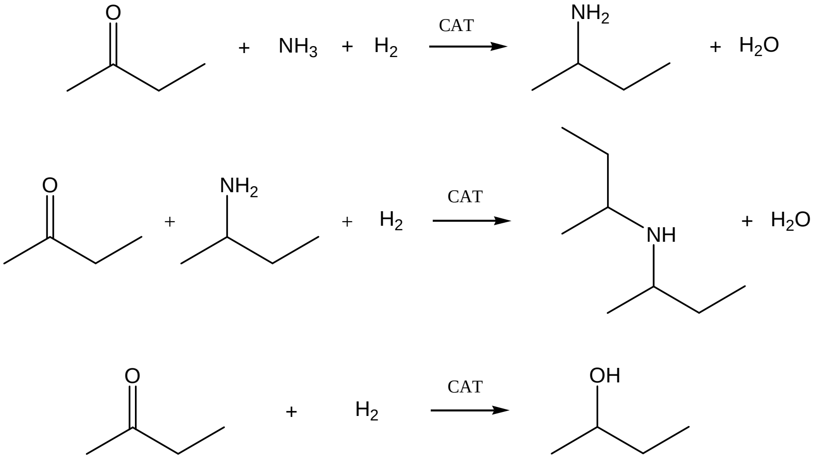
The progress of reaction in time was evaluated from the hydrogen consumption by measuring the hydrogen flow with a flow meter (BROOKS) having the pressure inside the autoclave controlled by a pressure regulator (BROOKS). Liquid sampling was used for monitoring the evolution of products in time.

Reductive amination of MEK (>99%, Merck) and butanal (>99%, Merck) were conducted mostly at 50 bar and 80 ºC. The products were analyzed by using a Hewlett Packard 5890A gas chromatograph equipped with a DB Wax 1701 column and FID detector. Pure amines (butylamine, di-butylamine, tri-butylamine, sec-butylamine and di-sec-butylamine) were used for the identification of the main products in the reaction mixtures. GC/MS analyses were performed in order to identify reaction intermediates. The metal leaching was followed by XRF analysis of the filtered reaction mixtures.

Experiments and calculations were done in order to find whether mass transfer rate limitations occurred or not for the highly active catalysts. According to the results obtained, mass transfer limitations of hydrogen diffusion from liquid to solid had no influence on the measured reaction rates.

RESULTS AND DISCUSSION

In the product mixtures resulted from the reductive amination of MEK with ammonia and hydrogen over supported noble metal catalysts were identified sec-butylamine, di-sec-butylamine and 2-butanol. Tri-sec-butylamine was never obtained. According to the analysis results, the reactions occurring in the reactor under the working conditions used (V_{EtOH} = 8 cm^3, n_{MEK} = 0.0222 mol, n_{NH3} = 0.3235 mol, n_{NH3}/n_{MEK} = 14.57, V_{EtOH}/V_{MEK} = 4, p = 50 bar, T = 353 K) are given in Scheme 1.



Scheme 1. Chemical reactions during the reductive amination of MEK.

In order to probe for mass transfer limitations, reductive amination experiments of MEK at different stirring speeds (1100 and 600 rpm), and at different catalysts concentrations were carried out. The experimental conditions and the results obtained for the reductive amination of methyl ethyl ketone on Rh/charcoal and Rh/HSA graphite catalysts are presented in Table 2.

The results on conversions, yields and rates of formation at different stirring speeds presented in Table 2 indicate that under the working conditions used, mass transfer limitations are unimportant in case of reductive amination of MEK over 5% Rh/HSA graphite and 5%Rh/charcoal.

Fig.1 illustrates the hydrogen consumption as a function of time for the tested catalysts.

Fig. 1 shows that Rh/charcoal is the most active catalyst, followed by Pt/HSA graphite, Rh/HSA graphite, Ru/HSA graphite while Pd/HSA graphite being the less active catalyst. The maximum rate of hydrogen consumption calculated from these curves for Rh/charcoal is: ~ $5 \cdot 10^{-8}$ mol/$cm^3 \cdot s$ and ~ $5 \cdot 10^{-9}$ mol/$cm^3 \cdot s$ for Rh/HSA graphite catalyst.

Table 2

Experimental conditions and results for the reductive amination of MEK on charcoal and graphite supported rhodium catalysts at different stirring speeds. n_M: moles of metal, $n_M = 1.11 \cdot 10^{-4}$ mol, Solvent: EtOH, $V_{EtOH} = 8$ cm^3, $n_{MEK} = 0.0222$ mol (2 cm^3), $n_{MEK}/n_M = 200$, $n_{NH3} = 0.3235$ mol, $n_{NH3}/n_{MEK} = 14.57$, p = 50 bar, T = 353 K.

Catalyst	t_{react} (min)	X (%)	Y_{pr} (%)	Y_{sec} (%)	$Y_{2\text{-}ol}$ (%)	r_{pr} (mol/mol·h)	r_{sec} (mol/mol·h)	$r_{2\text{-}ol}$ (mol/mol·h)
Rh/HSAgraph								
1100 rpm	60	98	86	0.4	12	175	0.7	23.9
600 rpm	65	98	85	0.7	10	170	1.3	19.8
600 rpm*	200	83	54	0.0	1	163	0.0	3.0
Rh/charcoal								
1100 rpm	8	99	98	0.4	0.6	1371	5.9	13.6
1100 rpm*	40	97	92	0.9	2.7	1384	40.8	12.7
600 rpm*	45	98	95	0.9	2.8	1262	36.8	11.3

X	conversion (molar percentage of MEK converted to different products).
Y	yield (molar percentage of MEK converted to the corresponding amine).
r	rate of product formation
*	$n_{Rh} = 2.22 \cdot 10^{-5}$ mol, $n_{MEK}/n_M = 1000$.

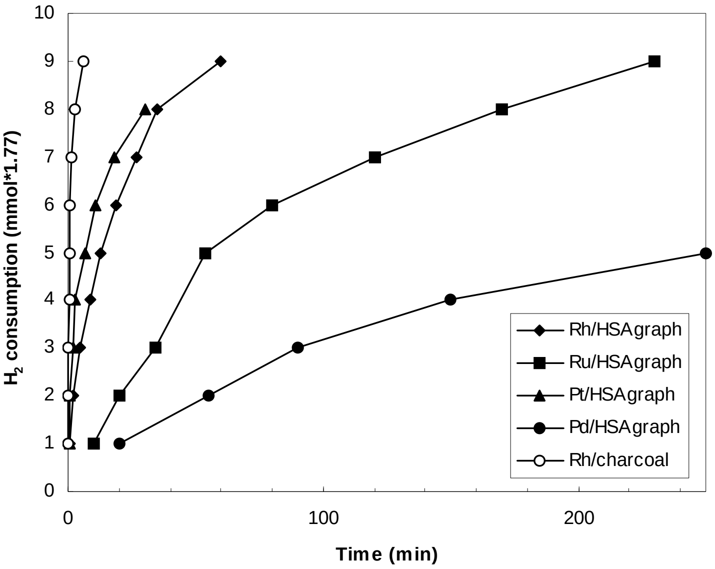
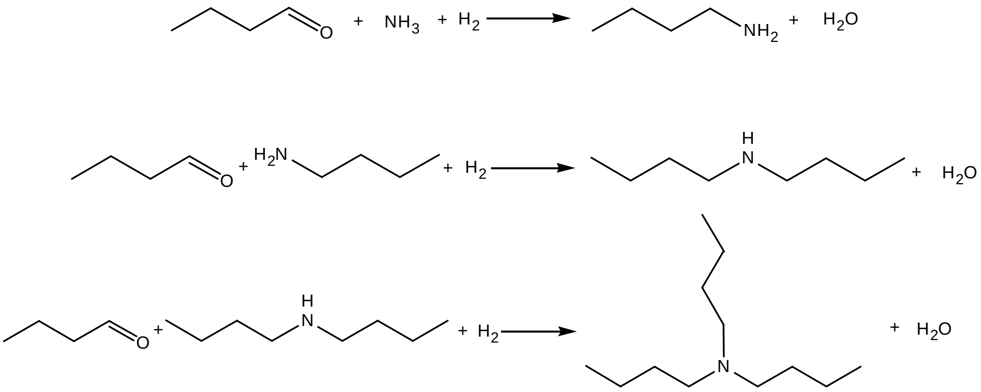


Fig. 1. Hydrogen consumption versus reaction time during the reductive amination of MEK on graphite and charcoal supported noble metal catalysts. n_M: moles of metal, $n_M = 1.11 \cdot 10^{-4}$, Solvent: EtOH, $V_{EtOH} = 8$ cm^3, $n_{MEK} = 0.0222$ mol, $n_{MEK}/n_M = 200$, $n_{NH3} = 0.3235$ mol, $n_{NH3}/n_{MEK} = 14.57$, p = 50 bar, T = 353 K.

In the product mixture resulted during the reductive amination of butanal with ammonia and hydrogen over supported noble metal catalysts butylamine, dibutylamine and tributylamine were identified. According to the obtained analysis results, the reactions occurring in the reactor under the working conditions used (V_{EtOH} = 8 cm^3, $n_{Butanal}$ = 0.0222 mol (2 cm^3), n_{NH3} = 0.3235 mol, $n_{NH3}/n_{Butanal}$ = 14.57, $V_{EtOH}/V_{Butanal}$ = 4, p = 50 bar, T = 323-353 K) are given in Scheme 2.



Scheme 2. Chemical reactions during the reductive amination of butanal.

The hydrogen consumption (normalized to moles of metal in the catalysts) indicates that Pt and Rh are the most active metals (Fig.2).

The very high activity of 5%Rh/charcoal relative to 5%Rh/HSA graphite (HSA = high surface area) can be attributed to the high surface area of the charcoal support, which resulted in a higher metal dispersion. The increased activity of 5%Pt/HSA graphite versus 5%Pt/LSA graphite can be attributed to the higher metal dispersion of the 5%Pt/HSA graphite catalyst.

The maximum reaction rate calculated from the hydrogen uptake for the 5%Rh/charcoal catalyst is $r_{max} = 2.2 \cdot 10^{-7}$ mol/$cm^3 \cdot$s and for the 5%Rh/HSA graphite catalyst is $r_{max} = 3.6 \cdot 10^{-8}$ mol/$cm^3 \cdot$s.

For the calculation of mass transfer rates of hydrogen from liquid phase to solid catalyst (considered as being the rate determinant step of mass transfer processes) the following equations were used [7]:

$$R_A = k_s a_p (A_l - A_s)$$

$$a_p = 6w/\rho_p d_p$$

where:

R_A	rate of hydrogen mass transfer from liquid-to-catalyst, mol/$cm^3 \cdot$s
k_s	liquid-to-catalyst mass transfer coefficient, cm/s
a_p	external area of particles per unit volume of reactor, cm^2/cm^3
A_l	concentration of A in the bulk liquid, mol/cm^3
A_s	concentration of A at the catalyst surface, mol/cm^3
w	catalyst mass per unit volume of the reactor, g/cm^3
ρ_p	density of the catalyst particle, g/cm^3
d_p	average diameter of the catalyst particles, cm

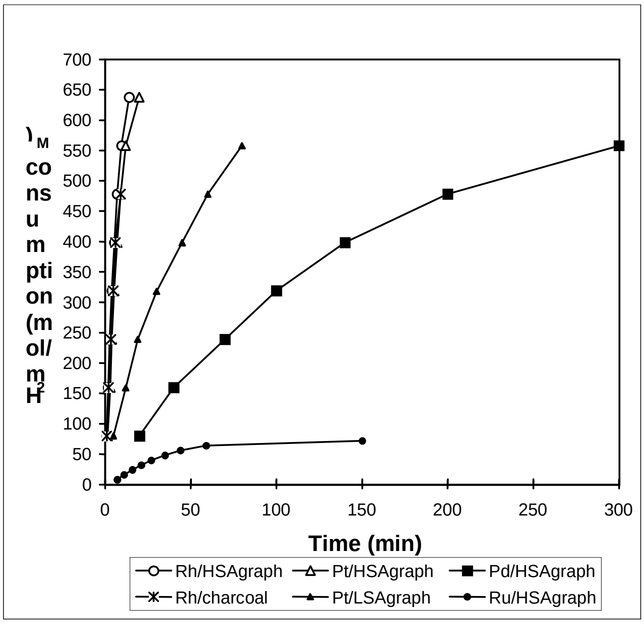


Fig. 2. Hydrogen consumption normalized to moles of metal as a function of reaction time for the reductive amination of butanal over carbon supported noble metal catalysts (n_M: moles of metal, $n_M = 2.22 \cdot 10^{-5}$ mol, $n_{Ru} = 2.22 \cdot 10^{-4}$ mol, $n_{Butanal} = 0.0222$ mol, $n_{NH3} = 0.3235$ mol, $n_{NH3}/n_{Butanal} = 14.57$, p = 50 bar, T = 353 K).

The correlation for k_s in agitated vessels proposed by Boon-Long *et al*. [7] can be given as below:

$$k_s = 0.046(D/d_p)(2\pi^2 d_p \rho_L d_T N/\mu_L)^{0.283}(\rho_L^2 g d_p^3/\mu_L^2)^{0.173} \cdot$$

$$\cdot(wV_L/\rho_L d_p^3)^{-0.011}(d_T/d_p)^{0.019}(\mu_L/\rho_L D)^{0.461}$$

where:

$d_p = 2.7 \cdot 10^{-3}$ cm for charcoal and $1.85 \cdot 10^{-3}$ cm for the graphite (diameter of the particle)
$D = 1.27 \cdot 10^{-4}$ cm^2/s, diffusion coefficient of A (hydrogen) in the liquid phase, cm^2/s.
$\rho_p = 0.4$ g/cm^3 for charcoal and 2.26 g/cm^3 for the graphite (apparent density)
$\rho_L = 0.6$ g/cm^3 (the density of the liquid)
$d_T = 4$ cm (the diameter of the tank)
w = 0.00114 g/cm^3 for the Rh/charcoal, and 0.00228 g/cm^3 for the Rh/HSA graphite (w = catalyst loading)
N = 18.33 s^{-1} (speed of agitation employed, s^{-1})
g = 980 cm/s^2
$\mu_L = 0.00504$ g/cm·s (viscosity of the liquid, g/cm·s)
$A_l = A_{H2} = (0.0864/22400 + 2/22400)$ mol/cm^3 (solubility of H_2 in EtOH) [8].
$A_s = 0.0$ mol/cm^3, solubility of H_2 in the solid catalyst
$V_L = 12$ cm^3, the volume of the liquid

Introducing these values in the equation of R_A, the rate of hydrogen mass transfer from the liquid to the surface of the 5%Rh/charcoal catalyst is:

$$R_A = 3.9 \cdot 10^{-5}\ \mathrm{mol/cm^3 \cdot s}$$

about 100 times higher than the measured maximum reaction rate, $r_{max} = 2.2 \cdot 10^{-7}$ $\mathrm{mol/cm^3 \cdot s}$ calculated from the hydrogen uptake for the reductive amination of butanal and around 1000 times higher than we got for MEK ($5 \cdot 10^{-8}$ $\mathrm{mol/cm^3 \cdot s}$). Even, at the minimum hydrogen solubility:

$$R_A = 1.6 \cdot 10^{-6}\ \mathrm{mol/cm^3 \cdot s}$$

The mass transfer rate of hydrogen from liquid to catalyst obtained for the 5%Rh/HSA graphite catalyst is:

$$R_A = 1.1 \cdot 10^{-5}\ \mathrm{mol/cm^3 \cdot s}$$

much higher compared to the measured maximum reaction rates for butanal on this catalyst ($r_{max} = 3.6 \cdot 10^{-8}$ $\mathrm{mol/cm^3 \cdot s}$) and for MEK ($5 \cdot 10^{-9}$ $\mathrm{mol/cm^3 \cdot s}$), calculated from the hydrogen uptake. For the lowest solubility value of hydrogen:

$$R_A = 8.7 \cdot 10^{-7}\ \mathrm{mol/cm^3 \cdot s}$$

According to calculations, mass transfer limitations are not influencing the kinetic measurements. However, to be sure about it, experiments with 1% Rh loading catalysts were also performed. The maximum reaction rates (normalized per mol metal) obtained on 1% Rh/HSA graphite were lower or almost identical to those measured on 5%Rh/HSA graphite catalyst.

CONCLUSIONS

Among the studied catalysts the Rh and Pt based ones show the highest activity in reductive amination of butanal and methyl ethyl ketone. This underlines the major role of metal in determining the activity and selectivity of the supported catalysts.

Charcoal appears to be a good catalyst support providing high activity and selectivity for the supported Rh catalyst (having high BET area and high metal dispersion) being significantly more active compared to Rh/graphite, emphasizing the important role of the support materials. The BET area and especially the metal dispersion have a strong influence on the catalyst activity for the reductive amination of butanal.

According to experimental and calculation results, mass transfer limitations have no influence on the kinetic measurements during three phase catalytic reductive amination of butanal and methyl ethyl ketone over carbon supported noble metals.

ACKNOWLEDGEMENT

Financial support from the DSM company is greatly appreciated.

REFERENCES

1. S. Yada, Y. Takagi and M. Hiyamizu, Nippon Kagaku Kaishi, 1995, (2), 107.
2. J. Bódis and J.A. Lercher, Studia-Chemia, Studia-Chem., 2002, **47**, 169.
3. J. Bódis and J.A. Lercher, Studia-Chemia, Studia-Chem., 2004, **49**, 53.
4. W. Bender, From Synthons to Bioactive Molecules: Efficient Strategies in Modern Lead structure Research, lecture at ICS-UNIDO Workshop on Trends and Applications of Combinatorial Chemistry and Combinatorial Technologies, Budapest, Hungary, October 15-18, 2001, pp. 20-46.
5. J. Bódis and J.A. Lercher, Confidential Reports to DSM Company, 1997-1998.
6. J.J.F. Scholten, A.P. Pijpers and A.M.L. Hustings, Catal. Rev.-Sci. Eng., 1985, **27**, (1), 151.
7. P.A. Ramachandran and R.V. Chaudhari, Three Phase Catalytic Reactors, in Topics in Chemical Engineering, volume 2, A series edited by R. Hughes, Gordon & Breach Science Publishers, New York-London-Paris, 1983.
8. W.F. Linke, Solubilities, Inorganic and Metal-Organic Compounds, volume I., Fourth Edition, D. Van Nostrand Company, Inc., Princeton, New Jersey, Toronto, London, New York, 1958.