



Tetrahedron Letters 44 (2003) 1507-1509

TETRAHEDRON LETTERS

Highly sustainable catalytic dehydrogenation of alcohols with evolution of hydrogen gas

G. B. W. L. Ligthart, R. H. Meijer, M. P. J. Donners, J. Meuldijk, J. A. J. M. Vekemans and L. A. Hulshof*

Eindhoven University of Technology, Laboratory of Macromolecular and Organic Chemistry, PO Box 513, 5600 MB Eindhoven, The Netherlands

Received 25 November 2002; revised 4 December 2002; accepted 4 December 2002

Abstract—The catalytic dehydrogenation of alcohols into aldehydes and ketones in the absence of H-acceptors was studied with several transition metal catalysts in order to develop a large-scale procedure. Applying $Ru(OCOCF_3)_2(CO)(PPh_3)_2$, the so called Robinson catalyst, several secondary alcohols could be dehydrogenated with high selectivity into the corresponding ketones in relatively short reaction times. Highly effective atom utilization could be realized avoiding solvents and giving hydrogen gas as the sole by-product. However, in contrast to Robinson's work the catalytic dehydrogenation of primary alcohols appeared to be problematic due to decarbonylation with concomitant catalyst deactivation and aldol condensation under the strong acid or basic conditions applied. © 2003 Elsevier Science Ltd. All rights reserved.

The development of catalytic oxidations under mild reaction conditions is highly appealing. The fine chemical industry invests strong effort in the development of sustainable technologies, based on environmental acceptability. The criteria include high atom efficiency, formation of little inorganic waste and selective synthesis of the desired products. Usually, salts represent the main waste.^{1,2} Moreover, the reactions are often performed in environmentally unfriendly solvents, typically chlorinated hydrocarbons.³ Here we wish to report our initial results with an environmentally benign catalytic oxidation methodology using transition metal catalysts.⁴ Homogeneous systems capable of catalyzing these reactions are rare. Inspired by the work of Robinson et al.⁵ in 1975, the feasibility of the dehydrogenation of primary and secondary alcohols was studied with respect to avoiding H-acceptors and developing a large-scale synthesis using their $Ru(OCOCF_3)_2(CO)(PPh_3)_2$ catalyst. Although application of the catalyst is known to produce hydrogen gas, to our surprise no systematic and quantitative study with respect to the fate of the alcohols was presented,^{4–7} and to the best of our knowledge such information was not reported elsewhere. Instead, the specific activity of the Robinson catalyst in hydrogen production resulting from dehydrogenation of the primary alcohols ethanol, n-propanol and n-butanol was disputed.⁷

Compared to classical oxidations, the catalytic oxidation accompanied by elimination of hydrogen gas will enhance the atom efficiency from $\sim 50\%$ up to $\sim 98\%$. The catalytic dehydrogenation of secondary alcohols described in this paper can schematically be represented by Eq. (1).

The applied Ru(OCOCF₃)₂(CO)(PPh₃)₂ catalyst could be prepared in situ from commercially available chemicals. as reported by Robinson et al.⁴⁻⁶ In addition to their work with primary alcohols such as ethanol, *n*propanol to *n*-hexanol and benzyl alcohol and secondary alcohols such as isopropanol and cyclohexanol, we found that Ru(OCOCF₃)₂(CO)(PPh₃)₂ also catalyzes selective hydrogen elimination from long chain aliphatic secondary alcohols. Ketones were produced in high yields and in relatively short reaction times at 130°C using 1 mol% of catalyst with respect to the substrate. In the absence of solvents only 12–18 equiv. (with respect to the catalyst) of CF₃CO₂H were required. All reaction mixtures, started as a bright yellow solution, turned dark red after a few minutes



* Corresponding author.

0040-4039/03/\$ - see front matter @ 2003 Elsevier Science Ltd. All rights reserved. PII: S0040-4039(02)02842-3

and changed again to bright yellow at the end of the reaction. The catalyst could be recycled three times without significant loss in catalytic activity.

Furthermore, no loss in catalytic activity was observed when the catalyst came in contact with water. The turnover number could well exceed 200 in the case of the oxidation of 2-octanol.⁸ The results are depicted in Table 1. Very low concentrations of H_2 in boiling alcohol as a result of immediate removal ensure that the reverse reaction, i.e. hydrogenation of the ketone or aldehyde, does not play a significant role.

The dehydrogenation of secondary alcohols in the absence of a H-acceptor to produce ketones can be rationalized with the catalytic cycle for the production of hydrogen gas from simple alcohols like ethanol or 2,3-butanediol as proposed by Dobson and Robinson. These authors stated that the catalysis is promoted by the addition of small amounts of free acid (CF₃CO₂H) and is inhibited by aldehyde or ketone and large amounts of acid.⁶ However, in our hands, in situ preparation from 1 mol% RuH₂(CO)(PPh₃)₃ and 12–18 molar equiv. (with respect to the catalyst) of CF₃CO₂H yielded the highest selectivities in the dehydrogenation of secondary alcohols. To obtain mechanistic information, a ruthenium complex formed during the dehydrogenation of 2octanol with 18 molar equiv. of CF₃CO₂H was isolated after distillation of the reaction mixture. The mass (m/z)of 877 obtained from MALDI-TOF measurements was assigned to $Ru(OCOCF_3)_2(CO)(PPh_3)_2$ thus proving the statement of Robinson et al.⁶

Four acids of varying strength were investigated in the dehydrogenation of 2-decanol and 2-octanol using $RuH_2(CO)(PPh_3)_3$ as the catalyst precursor. The experiments were performed in the presence of 1 mol% $RuH_2(CO)(PPh_3)_3$, with different stoichiometries of acid compared to the catalyst but always at 130°C in the absence of solvent. All experiments were stopped after 5 h. The results of these experiments are collected in Table 2.

Due to the high volatility of CF_3CO_2H (bp 72°C)—it evaporates from the reaction mixture—acids with higher boiling points were investigated. Small amounts of *p*toluenesulfonic acid (*p*-TsOH) as relatively strong acid and varying amounts of trichloroacetic acid and acetic acid as weaker acids were tested as well. With an increasing amount of acid the dehydrogenation rate increases but the selectivity to the corresponding ketone decreases; presumably due to acid-catalyzed aldol condensation of the ketone. In contrast, the selectivity and rate of dehydrogenation improve with increasing amounts of the less strong acid CF_3CO_2H indicating a plateau value for acid amounts larger than 12 equiv.

When even less strong acids are used, hydrogen gas is released from the metal center at a lower rate and consequently the overall dehydrogenation is slower. This observation can be rationalized by a more limited ability to protonate the metal hydride compared to CF_3CO_2H and *p*-TsOH.

In contrast to the claims of Dobson and Robinson, low conversions and selectivities were observed when primary

Table 1. Ru(OCOCF₃)₂(CO)(PPh₃)₂-catalyzed hydrogen elimination from secondary alcohols at 130°C⁹

Entry	Substrate	Time (h)	Conv. (%)	Yield (%)	Sel. (%) 96	
1	2-Octanol	5	84	81		
2	2-Decanol	5	86	82	95	
3	1-Phenylethanol	2	94	59	63	
	1-Phenylethanol ^a	5	54	49	91	
4	4-tert-Butylcyclohexanol	5	53	34	64	
5	Menthol	25	73	51	70	
6	Cyclohexanol	5	85	80	94	

^a 24% v/v of 1-phenylethanol in toluene, 5 molar equiv. (with respect to the catalyst) of CF₃CO₂H, 110°C.

Table 2.	Effect of	of properties	and amou	nt of ac	id on	the catalytic	e dehydrogena	tion of 2	2-decanol	or 2	2-octanol ^a
----------	-----------	---------------	----------	----------	-------	---------------	---------------	-----------	-----------	------	------------------------

Acid	pK_a in water	Eq. acid	Conv. (%)	Yield (%)	Sel. (%)
p-CH ₃ C ₆ H ₄ SO ₃ H ^b	-6.5	1	77	55	71
		2	97	64	66
		4	100	44	44
CF ₃ CO ₂ H ^c	0.23	0	58	24	41
		2	52	33	63
		6	79	54	68
		12	86	82	95
		18	84	81	96
CCl ₃ CO ₂ H ^b	0.65	5	40	33	83
CH ₃ CO ₂ H ^b	4.76	12	62	49	79

^a Conditions: neat, 130°C, 1 mol% RuH₂(CO)(PPh₃)₃, 5 h.

^b 2-Octanol was used as substrate; some dehydration to 2-octene was observed.

^c 2-Decanol was used.

alcohols were dehydrogenated. The aldehydes probably decarbonylate and produce CO that poisons the catalyst as was demonstrated by Geoffroy and Pierantozzi.¹⁰ Furthermore, the strong acidic conditions employed are known to catalyze aldol condensation and dehydration. Milder reaction conditions have to be found to render the oxidation of primary alcohols successful. These milder reaction conditions can probably be achieved by varying the nature of either the phosphine or carboxylato ligands.

Conclusions

An environmentally benign dehydrogenation methodtransition metal ology using catalysts like $Ru(OCOCF_3)_2(CO)(PPh_3)_2$ has been developed. The criteria include high atom efficiency as well as formation of little inorganic and organic waste. Several secondary alcohols have been selectively dehydrogenated into the corresponding ketones in relatively short reaction times and in the absence of solvents. Furthermore, the catalysts used in these reactions could be prepared in situ from commercially available chemicals. The catalyst could be recycled three times without significant loss in catalytic activity. As the best acid for the dehydrogenation CF₃CO₂H has been selected.

For secondary alcohols the intrinsic catalytic activity will be studied further by fine-tuning the ligands of the Robinson catalyst.

Acknowledgements

We gratefully acknowledge the financial support by the Ministry of Economic Affairs within the framework of the Innovation Oriented Research Program on Catalysis (IOP-Catalysis). We thank Ir. J. van Buijtenen for his assistance in various parts of this study.

References

- 1. Murahashi, S.-I.; Takaya, H. Acc. Chem. Res. 2000, 33, 225.
- 2. Hoelderich, W. F. Catal. Today 2000, 62, 115.
- 3. Sheldon, R. A. J. Mol. Catal. A. 1996, 107, 75.
- Robinson, S. D.; Uttley, M. F. J. Chem. Soc., Dalton Trans. 1973, 1912.
- Dobson, A.; Robinson, S. D. J. Organomet. Chem. 1975, 87, C52.
- (a) Dobson, A.; Robinson, S. D.; Uttley, M. F. J. Chem. Soc., Dalton Trans. 1975, 370; (b) Dobson, A.; Robinson, S. D. Inorg. Chem. 1977, 16, 1321; (c) Dobson, A.; Robinson, S. D. Inorg. Chem. 1977, 16, 137.
- (a) Rybak, W. K.; Ziolkowski, J. J. J. Mol. Catal. 1981, 11, 365; (b) Jung, C. W.; Garrou, P. E. Organometallics 1982, 1, 658.
- 8. Based on once repeated use of catalyst.
- 9. All catalytic oxidation experiments were performed in a dry, oxygen-free argon atmosphere. A typical experiment consisted of the following. An oven-dry 40 ml Radley carousel reaction tube was flushed with argon before it was charged with $RuH_2(CO)(PPh_3)_3$ (91.8 mg, 0.10 mmol) and CF₃CO₂H (205 mg, 1.8 mmol). A mixture of alcohol (10.00 mmol) and internal standard (1,3,5-tri-tert-butylbenzene, 81 mg, 0.33 mmol) was added to the in situ prepared catalyst. The reaction tube was placed in a 12 tube Radley reaction carousel and the mixture was heated to 130°C and stirred for several hours. Small aliquots of reaction mixture were taken for GC analysis. The conversions and yields were determined with GLC. GLC analyses were performed using a Zebron ZB-35 column on a Perkin Elmer Autosystem. Conversions and yields were determined by using 1,3,5-tritert-butylbenzene as internal standard. GC/MS measurements were obtained with a Shimadzu GC/MS-QP5000 using a Zebron ZB-35 column. MALDI-TOF spectra were obtained on a PerSeptive Biosystems Voyager DE PRO spectrometer using α -cyano-4-hydroxycinnamic acid as a matrix. The products were characterized (GLC) by comparison with authentic samples (Table 2). Recycling of the catalyst was established by evaporating the reaction mixture followed by addition of fresh alcohol.
- (a) Pierantozzi, R.; Geoffroy, G. L. *Inorg. Chem.* **1980**, *19*, 1821; (b) Geoffroy, G. L.; Pierantozzi, R. J. Am. Chem. Soc. **1976**, *98*, 8054.