PURE VACUUM.
NOTHING ELSE.

NEW

10^{-3} mbar vacuum range
+ 100% oil-free
+ Chemically resistant
+ No wear parts

VACUU·PURE®

Learn more

www.vacuubrand.com/vacuu-pure

vacuubrand®

A Mechanistic Study on Alcohol Oxidations with Oxygen Catalysed by TPAP-Doped Ormosils in Supercritical Carbon Dioxide

Sandro Campestrini,[a,*] Massimo Carraro,[a] Rosaria Ciriminna,[b] Mario Pagliaro,[b] Umberto Tonellato[a]

[a] Università di Padova, Dipartimento di Scienze Chimiche; CNR, Istituto per la Tecnologia delle Membrane, via Marzolo 1, 35131 Padova, Italy
Fax: (+39)-49-827-5239, e-mail: sandro.campestrini@unipd.it
[b] Istituto per lo Studio dei Materiali Nanostrutturati, CNR, via Ugo La Malfa 153, 90146 Palermo, Italy

Received: December 1, 2004; Accepted: March 4, 2005

Abstract: The heterogeneous oxidation of various alcohols with oxygen catalysed by TPAP-doped ormosils in $scCO_2$ at 75 °C and 22.0 MPa has been studied in detail. Sol-gel segregation of TPAP into the inner porosity of an organically modified silica (ormosil) xerogel along with the use of a reaction medium which does not dissolve the catalyst, prevents aggregation of oxidation-inactive ruthenium derivatives without the need of chemical tethering. Thus, at least 140 TONs may be obtained in the oxidation of primary alcohols with the formation of aldehydes as sole reaction products. Investigation of the oxidation mechanism shows that the catalytic process exhibits a first-order dependence on the amount of catalyst, a fractional order on the alcohol concentration and a negative order for oxygen pressures higher than 0.2 bar. Evidence is presented for an associative oxidation mechanism simultaneously involving TPAP, organic substrate and oxygen.

Keywords: carbon dioxide; ormosil; oxidation mechanism; oxygen; ruthenium; sol-gel

Introduction

Alcohol oxidation yielding ketones and aldehydes is a chemical transformation of primary importance in the chemical industry, carbonyl compounds being precursors of a variety of valuable fine chemicals including drugs, vitamins and fragrances.[1] Traditional alcohol oxidations, on the other hand, are still carried out by industry with stoichiometric amounts of toxic and hazardous metal oxidants such as dichromate and permanganate in volatile organic solvents producing enormous amounts of waste.[2] Societal demand for fundamental chemical transformations that are not harmful to the environment is pressing, and an economically and environmentally viable replacement of current alcohol oxidation processes with heterogeneous catalytic conversions is a scientific challenge for chemists both in industry and academy.[3]

Obviously, the utilization of oxygen (and even better of air) as stoichiometric oxidant for the selective oxidation of organics yielding water as sole by-product is the final, ideal goal of prolonged research efforts that in the last few years have resulted in a number of highly selective catalytic conversions based on Ru,[4] Pd,[5] Cu,[6] Co,[7] V,[8] Os[9] catalytic species.

Among these aerobic metal catalysts, ruthenium is probably the most promising thanks to its impressive selectivity in the presence of several oxidisable groups;[4] in particular, the species tetra-*n*-propylammonium perruthenate (TPAP) is a very efficient and selective catalyst for the aerial oxidation of primary, secondary, benzyl and alkyl alcohols either dissolved in conventional organic solvent[10–12] or even in an ionic liquid.[13]

Similarly to what happens with many catalytic transition metal ion pairs,[14] sol-gel encapsulation of TPAP into ceramic matrices affords heterogeneous aerobic catalysts of different efficiency either for conversions in conventional solvent[15,16] or in carbon dioxide in the supercritical state,[17] an intrinsically non-toxic and environmentally benign reaction medium ideally suited for heterogeneous catalytic applications in the fine chemicals industry.

In all cases, most functional groups, i.e., carbon-carbon double bond, epoxy, indole, acetal functions, etc., remain unaffected by TPAP and high yields of carbonyl compounds are isolated.[10,11,18] However, in spite of the well established synthetic scope of TPAP as a stoichiometric oxidant and aerobic catalyst, little is known about the intimate mechanism of alcohol oxidations.

DOI: 10.1002/adsc.200404365

In a mechanistic study[19] on the stoichiometric alcohol oxidations by perruthenate anion in water, Lee and Congson suggested that the oxidation proceeds through the formation of an intermediate involving a bond between Ru(VII) and the α-alcoholic carbon, followed by fragmentation into a radical species which is further oxidised to the final carbonyl product.

This radical mechanism is also supported by Griffith's study on diol oxidations catalysed by perruthenate in the presence of sodium bromate (BrO_3^-) and dipersulphate ($S_2O_8^{2-}$) as terminal oxidants in water at alkaline pH.[20] However, on going from aqueous to organic solvents, the oxidative process seems to be forced to follow a different pathway. Indeed, contrary to what happens in aqueous solution,[19] TPAP oxidizes cyclobutanol to cyclobutanone in organic media in good yields[18] thus suggesting that homolytic processes do not play a major role, at least in stoichiometric oxidations. Moreover, Lee has further showed that the stoichiometric oxidation of propan-2-ol by TPAP in CH_2Cl_2 is strongly *autocatalytic* and ascribed this outcome to the coordination of unreacted TPAP with colloidal particles of the product (RuO_2).[21]

More recently Kozhevnikov has demonstrated that in the catalytic oxidation of primary alcohols with oxygen catalysed by TPAP in toluene, in addition to the expected products – namely aldehydes and minor amounts of carboxylic acids – the reaction mixtures contain by-products arising from solvent oxidation and NPr_4^+ degradation.[22] Furthermore, the catalytic process exhibits an initial faster stage followed by slower kinetics which suggests the involvement of *different* active ruthenium species. In the same study, the authors confirmed the impossibility of catalyst recycling for homogeneous aerobic oxidation after a maximum TON of *ca.* 20.

Extending our mechanistic kinetic studies on the oxidation of various alcohols by oxygen in the presence of a TPAP-doped ormosil in $scCO_2$,[17] we reasoned that physical segregation of $[NPr_4^+][RuO_4^-]$ ion pairs into the glass framework would prevent catalyst and/or its derivatives self-aggregation, thus simplifying the kinetic analysis of the system.

In addition, the utilization of $scCO_2$ as reaction medium allows us to work in a single phase as far as it concerns the substrate and the terminal oxidant, namely gaseous oxygen. Based on the new results reported in the following, we propose a mechanistic heterolytic pathway in which O_2 coordinates to the ruthenium centre and then dehydrogenates the alcoholic substrate.

Results and Discussion

Carbonyl compounds can be efficiently synthesised in $scCO_2$ by alcohol oxidation with molecular oxygen catalysed by TPAP-doped ormosils, whose activity is largely superior to perruthenate encapsulated within un-modified silica. These catalysts are prepared as previously described[17] by sol-gel entrapment of TPAP in silica glasses obtained using methyltrimethoxysilane (MTMS) and tetramethyl orthosilicate (TMOS) as precursors of the final xerogel. Catalysts with various surface hydrophobicities are easily obtained by varying the relative amount of methyl-modified precursor utilised in the synthesis of the xerogels (i.e., 0%, 25%, 75%, 100% of MTMS), whereas catalytic doped glasses with different pore sizes and entrapment modalities of TPAP are obtained by varying the process employed for the xerogels preparation, i.e., the amount of water and the presence of NaF.[17] The higher suitability of $scCO_2$ as reaction medium for aerobic oxidation of alcohols with respect to conventional liquid solvents of comparable polarity is revealed by the fact that TPAP encapsulated in unmodified SiO_2 is practically inactive in toluene[16] whereas it exhibits some activity in $scCO_2$.[17a] Results obtained in $scCO_2$ indicate that the best performing catalysts require both a high degree of surface hydrophobicity as well as high amounts of water and co-solvent in the sol-gel polycondensation process and therefore we utilised in this study a 75% methylated silica prepared according to protocol A (see Experimental Section) named **TP-Me3A**.

The catalytic oxidations of alcohols were performed in a stainless steel, 10-mL reaction vessel at a final total pressure of 22.0 MPa and at 75 °C, in the presence of O_2 (0.2–7 bar at 25 °C) and **TP-Me3A** as catalyst. The molar ratios of the components of the reaction mixtures were approximately TPAP/alcohol/oxygen = 1/10–200/50–350; in which the oxygen excess over substrate and the final pressure of 22 MPa were used to ensure a complete conversion of benzyl alcohol and complete solubility of the substrate, respectively.

The corresponding rate constants ($k_{cat.}$) were obtained from integrated pseudo-first-order plots, i.e., $\ln([\text{aldehyde}]_{t=\infty} - [\text{aldehyde}]_{t=t})$ *vs.* time, which are linear up to 80–90% reaction as shown in Figure 1.

In particular, the $k_{cat.}$ values reported represent the slopes of such a plot. The linearity of the plots confirms that catalyst deactivation does not occur, at least in the time intervals examined. When the highest alcohol over TPAP ratio was used (*ca.* 200), a deviation from linearity is observed, thus suggesting a possible catalyst deactivation or even oxygen starving. In this case the $k_{cat.}$ was calculated taking into account only the linear part of the plot and it can be considered as an initial rate. Table 1 lists the results of some experiments aimed at evaluating the reproducibility of the catalytic reactions and the kinetic order in TPAP.

A first, relevant feature of these catalyzed reactions is the extremely high *selectivity* observed for the aldehyde formation. A rationale for this outcome is that the highly hydrophobic catalyst employed *spills out* the water formed during alcohol oxidation, thus preventing aldehyde hydration and consequently over-oxidation to car-

Table 1. Oxidation of benzyl alcohol (4.83×10^{-2} mmol) with oxygen (1 bar at 25 °C) catalysed by ormosil **TP- Me3A** (content of TPAP: 0.5×10^{-2} mmol per 100 mg), in $scCO_2$ at 75 °C and 22 MPa.

Entry	**TP-Me3A** [mg]	$k_{cat.} \times 10^2$ min^{-1}	$k_{cat.} \times 10^2$ min^{-1} (average)	Alcohol conversion [%]	Benzaldehyde yield [%]
1	100	4.66			
2	100	4.13			
3	100	3.45	4.08	100	100
4	20	0.99			
5	20	0.64			
6	20	0.77	0.8	98.2	98.1
7	10	0.29		97.0	96.7
8	5	0.056		71.0	70.5

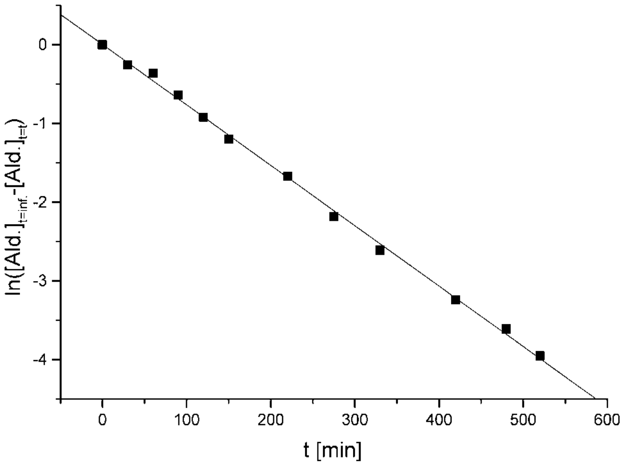


Figure 1. Plot of log([aldehyde]$_{t=\infty}$ – ([aldehyde]$_{t=t}$) *vs.* time in the oxidation of benzyl alcohol (4.83×10^{-2} mmol) with oxygen (1 bar at 25 °C) catalysed by 20 mg of **TP-Me3A** (TPAP content of 1.0×10^{-3} mmol) in $scCO_2$ at 22 MPa and 75 °C.

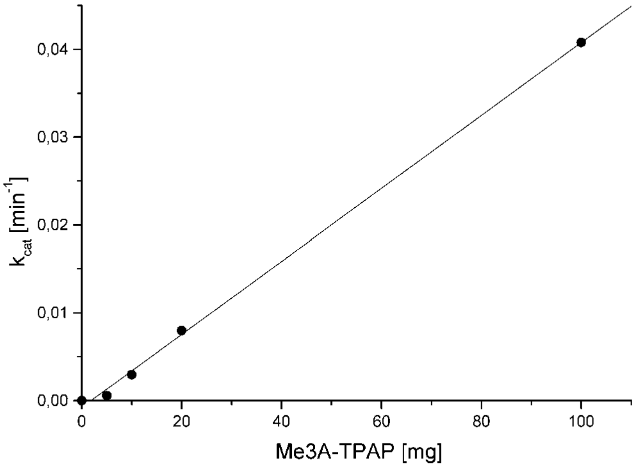


Figure 2. Kinetic order in catalyst relative to benzyl alcohol oxidation with O_2 (1 bar at 25 °C) catalysed by **TP-Me3A** (content of TPAP: 0.5×10^{-2} mmol per 100 mg ormosil), in $scCO_2$ at 75 °C, and 22 MPa.

boxylic acid. Moreover, $scCO_2$ may help in water removal through its well known ability of drying solid matrices. Entries 1–3 and 4–6 in Table 1 indicate a fairly good agreement in the measurement of pseudo-first-order constants in repeated experiments. In fact, it should be noted that the oxidative process is entirely heterogeneous, with the leach-proof catalyst being immiscible in the supercritical CO_2 phase; therefore, some deviations could be expected due, for instance, to the non-homogeneity in the catalyst particles used in different experiments.

A clear *activity enhancement* is observed upon sol-gel encapsulation since a 1 mol % catalytic amount of entrapped TPAP can now be used to afford high yields of benzaldehyde (entry 7), while with homogeneous perruthenate in solution a minimum of 10 mol % is required to observe optimal yields.[10,11] Indeed, entry 8 has a turnover number of 140 which is one of the highest thus far reported for an Ru-based aerobic catalyst.

Finally, the first order kinetics in catalyst (Figure 2) shows another unique feature of sol-gel entrapped compared to traditional solid catalysts obtained by heterogenisation of a material's external surface, which in general do *not* show a first order law dependence for catalyst.

Kinetic data for the oxidation of benzyl and several other alcohols under different experimental conditions are shown in Table 2.

Entries 9–11 indicate a linear dependence of initial velocities (R_o) for benzyl alcohol oxidation *versus* substrate concentrations (Figure 3), at least for the lowest values, thus suggesting first order kinetics in substrate.

At the highest alcohol concentration investigated, a negative deviation from linearity is observed, which might point to substrate coordination to the catalyst. Unfortunately, the limited alcohol solubility in the reaction medium limits the exploration of a wider concentration range.

Entries 12–14, referring to experiments carried out at varying partial oxygen pressures, show a negative dependence of rate constants on oxygen concentration (Insert in Figure 3). Comparison between entries 14, 16 and 19, 20 shows the higher reactivity of primary with respect to secondary hydroxyl functions in the oxidation of both

Table 2. Oxidation of various alcohols with oxygen catalysed by **TP-Me3A** (content of TPAP: 0.5×10^{-2} mmol each 100 mg of ormosil) in $scCO_2$ at 75 °C and 22 MPa.

Entry	Substrate [$mmol \times 10^2$]	**TP-Me3A** [mg]	PO_2 [bar]	$k_{cat.} \times 10^4$ [min^{-1}]	$R_o \times 10^6$ [$M\ min^{-1}$]
9	Benzyl alcohol [9.66]	5	1.0	4.74	5.72
10	Benzyl alcohol [4.83]	5	1.0	5.63	3.40
11	Benzyl alcohol [1.21]	5	1.0	4.43	0.67
12	Benzyl alcohol [4.83]	5	0.21	8.56	5.16
13	Benzyl alcohol [4.83]	5	7.0	4.43	2.68
14	Benzyl alcohol [4.83]	10	1.0	29.40	17.75
15	1-*D*-Benzyl alcohol [4.83]	10	1.0	17.60	10.65
16	1-Phenylethanol [4.83]	10	1.0	10.2	6.16
17	3-Chlorobenzyl alcohol [4.83]	10	1.0	31.4	18.96
18	4-Methylbenzyl alcohol [4.83]	10	1.0	19.3	11.65
19	1-Octanol [4.83]	10	1.0	7.0	4.23
20	2-Octanol [4.83]	10	1.0	2.9	1.75
21	Benzyl methyl ether [4.80]	10	1.0	n.r.	n.r.

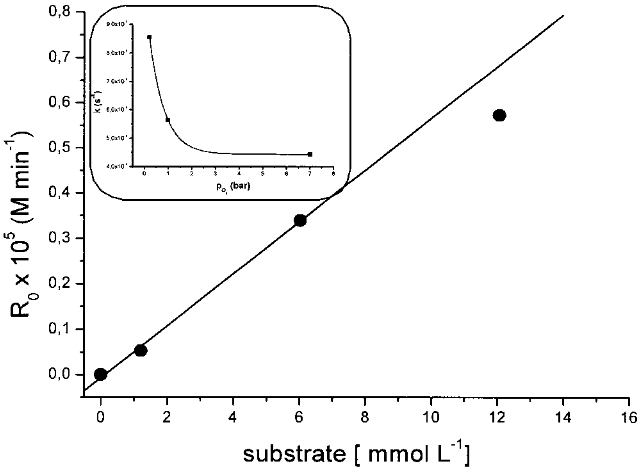


Figure 3. Kinetic order in substrate and oxygen (insert) for benzyl alcohol oxidation with O_2 catalysed by **TP-Me3A** (content of TPAP: 0.5×10^{-2} mmol per 100 mg of ormosil), in $scCO_2$ at 22 MPa and 75 °C.

benzyl and alkyl alcohols, which is a well established feature of TPAP in stoichiometric oxidations.[11,15] A corollary of this outcome is that the active catalytic species should be the perruthenate anion RuO_4^- and not other ruthenium species produced in the course of the process.

Interestingly, under the experimental conditions where smooth alcohol oxidation is observed, the oxidation of benzyl methyl ether (run 21) does *not* occur, suggesting that substrate coordination to TPAP takes place through the formation of an Ru–O bond rather than an Ru–C bond.

In order therefore to gather further information on the intimate mechanism of alcohol dehydrogenation, the effect of a few substituents on the oxidation rate of different benzyl alcohols has been studied (entries 14, 17, 18). The number of derivatives examined was limited by the scarce solubility in $scCO_2$ of other potentially useful substrates, i.e., *p*-nitro- and *p*-methoxybenzyl alcohols.

The rate constants determined by individual experiments may be correlated in a Hammett plot with the appropriate sigma values. The linear correlation among the three points is rather poor (R = 0.82) and therefore we will not speculate on the absolute value of the resulting Hammett rho value (+0.34), nor on the significance of curved Hammett plot. However, the positive sign of rho is worthy of note which is, in effect, opposite to that found in benzyl alcohol oxidations with oxygen catalyzed by metallic Ru,[4] thus corroborating the hypothesis that in our system RuO_4^- is the active species throughout the catalytic process.

Moreover, the partial *negative* charge developed on the benzyl carbon in the transition state nicely matches the peculiar reactivity of TPAP towards primary alcohols, indicating that the superior reactivity of primary alcohols is due to electronic rather than steric factors.

Entries 14 and 15 in Table 2 show that benzyl alcohol and its isotopically marked derivatives react at different rates, thus determining a kinetic isotopic effect (KIE) of 1.67. This value is rather small for a primary KIE, but it should be considered that the isotopically marked substrate used, namely PhCHDOH, still bears a hydrogen atom on the alkyl carbon and therefore it can lose either the deuterium atom giving PhCHO, or the hydrogen, affording PhCDO. As a consequence, the deuterium substitution is reflected only partially in the kinetic measurement leading to a KIE value lower than expected.

In order therefore to get a more realistic KIE, we determined the extent of hydrogen removal relative to deuterium by the ratio PhCDO/PhCHO formed in the course of PhCHDOH oxidation assessed by mass spectrometry. This would be easily done by considering the mass peak generated only by PhCHO and a second one generated by PhCDO only. Unfortunately, this is the case only for the 106 mass peak (M_{PhCHO}) generated by PhCHO, while all other peaks are resulting from the

Table 3. Values of PhCDO/PhCHO determined by means of two different mass peaks ratios [105/106 = (D – 2)/M and 107/106 = D/M] in various samples taken at appropriate times.

	60′	169′	236′	300′	1303′	1412′	1502′	Average
(D – 2)/M	1.89	1.92	1.91	1.86	1.91	1.86	1.83	1.88
D/M	2.13	2.14	2.14	2.13	2.12	2.08	2.07	2.12

contributions of both species. However, it is still possible to separate the two contributions by knowing the contribution of pure PhCHO. By solving these calculations for the 107 (M_{PhCDO}) and 105 ($M_{PhCDO-2}$) mass peaks and for seven samples of the reaction mixture taken at various times, two sets of KIE values were obtained (Table 3).

In particular, from the 105/106 ratio an average KIE of 1.88 is obtained while from the 107/106 ratio the average value calculated is 2.12, giving an overall average of 2.0.

The value thus determined is, as predicted, higher than that measured through the ratio of the kinetic constants, and should be compared with the maximum theoretical value for a primary KIE of 4.6 at 75 °C. A KIE value of 2.0 clearly indicates that hydrogen abstraction from the α carbon occurs in the rate-determining step of alcohol oxidation.

The results of the present work with sol-gel entrapped TPAP further demonstrate the validity of sol-gel encapsulation as a means for preparing highly efficient catalysts *and* of $scCO_2$ as advantageous alternatives both to chemical tethering[23] for the heterogenisation of perruthenate as well as to volatile organic solvents which, as typical VOCs, upon reaction must be disposed of according to strict regulations. In fact, while the reactant alcohol and O_2 molecules dissolved in $scCO_2$ easily enter the vast xerogel *inner* porosity (0.24 cm^3/g) where they react at the catalytic centre, TPAP itself remains insoluble in $scCO_2$ and is therefore scarcely prone to any of the self-aggregation phenomena which are typical of Ru-mediated oxidations.

In the attempt to elucidate the pathway of TPAP inactivation, we thus carried out catalyst recycle experiments recovering the catalyst from $scCO_2$ medium and washing it with various organic solvents.

Depending on the solvent utilised, the results in Figure 4 show that after only 10 TONs performed in the course of the first experiment, the catalyst retains only 10–40% of the initial efficiency in the second experiment (first recycle). Such an efficiency drop continues with further recycling and after a total of five runs (four recycles) the catalyst becomes inactive.

Interestingly, the rate of catalyst degradation depends on the nature of the solvent used for recovering and *washing* the active material. In dichloromethane, which is a good solvent for unsupported TPAP, the inactivation takes place very quickly and already after the first recycle the catalyst is almost inactive. On the other hand, in diethyl ether and even more in hexane, where unsupported TPAP does not dissolve at all, the efficiency decay is noticeably slower.

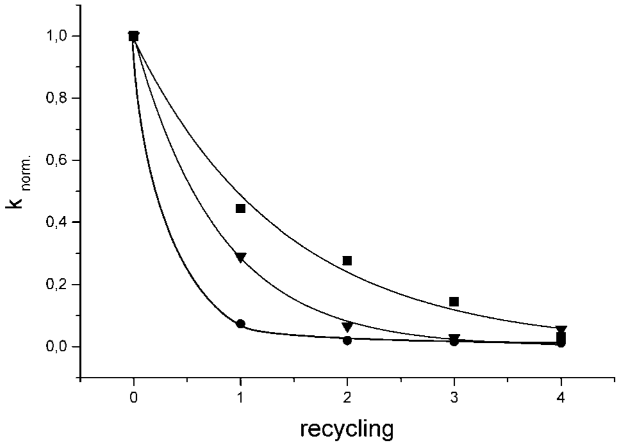


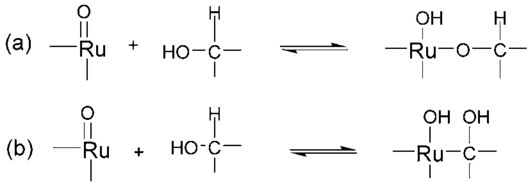
Figure 4. Dependence of normalised rate constants for benzyl alcohol (4.83×10^{-2} mmol) oxidation with O_2 (1 bar) catalysed by **TP-Me3A** (5.0×10^{-3} mmol) in $scCO_2$ at 22 MPa and 75 °C, as a function of catalyst recycling and washing solvent (■: ethyl ether; ▼: *n*-hexane; ●: dichloromethane).

These observations seem to corroborate the hypothesis of a TPAP inactivation caused by self-aggregation of Ru derivatives induced by the solvent, even though a chemical interaction with the solvent cannot be ruled out. In fact, when the catalyst is recovered and washed with CH_2Cl_2, a fast development of gas bubbles is induced and indeed a pungent smell of chlorine can be detected during desiccation. This is *not* the case with carbon dioxide, which is a superior reaction medium also due to its chemical inertness and is easily vented off by simple pressure release in the reaction system, leaving the solid catalyst physically and chemically unmodified, ready for reuse.

From a general mechanistic point of view, two alternatives should be taken into consideration in assuming a plausible mechanism for alcohol oxidations with O_2 catalysed by perruthenate. In particular, the oxidation may proceed either through a radical or a bielectronic, heterolytic mechanism. In addition, the coordination of the substrate to the catalyst may or may not be a prerequisite in both pathways.

The lack of any by-products arising from a hypothetic radical, together with a significant absolute Hammett's rho value, seem to *rule out* a free radical mechanism. As far as the involvement of an intermediate is concerned, the negative deviations from linearity in Ro *versus* substrate concentration might be indicative of a Michaelis–Menten type behaviour as well as of catalyst deactivation or even of the reached limit of substrate solubility. Hence, the oxidative addition of an alcohol to an oxo-metal double bond to give an intermediate product may involve either the O–H or C–H bond (see Scheme 1).

It has been reported that alcohol oxidations by ruthenate and perruthenate in basic *aqueous* solutions pro-



Scheme 1.

ceeds through *via* path (b) of Scheme 1.[21] In our system, however, the remarkable difference in reactivity between benzyl alcohol and the corresponding methyl ether clearly demonstrates that an organometallic derivative is *not* involved in the catalytic process. In fact, such a difference cannot be attributed to a steric effect since the secondary alcohol 1-phenylethanol (run 16), bearing steric hindrance similar to that of benzyl methyl ether, is smoothly oxidised under the same experimental conditions.

As a consequence, the difference in reactivity must originate from the different ability of the *two* substrates in generating a reactive intermediate *via* (a) of Scheme 1. Interestingly, the $k_{cat.}$ dependence on oxygen concentration shows a negative trend, similarly to what happens in aerobic alcohol oxidations catalysed by metallic Pd,[24] which is generally ascribed to the so-called "catalyst over-oxidation", a phenomenon probably involving the formation of palladium oxide on the metal surface which inactivates the catalyst.

On the other hand, in our system such a rationale cannot be invoked: in fact, in RuO_4^- the Ru metal centre is already present in one of its highest oxidation states. An alternative rationale, accounting for all the experimental findings, is that the alcohol oxidation is actually carried out by the oxygen in the coordination sphere of the metal centre. Such a ternary complex involving perruthenate, alcohol and oxygen reasonably accommodates in a single general mechanistic picture the first order kinetics in catalyst and the less-than-first order kinetics in both, alcohol and oxygen.

In fact, the inhibitory effect of high concentrations of both oxygen and alcohol might be the result of a decrease in the concentration of the effective 1:1:1 *ternary complex*, which leads to carbonyl products by an intramolecular hydride abstraction. Moreover, the occurrence of a primary KIE indicates that hydrogen abstraction from the α-carbon within the hypothesised intermediate is the rate-determining step of the overall process.

Conclusions

In conclusion, we have demonstrated that in aerobic oxidation of alcohols in $scCO_2$ TPAP-doped ormosils exhibit a superior catalytic performance relative to the same homogeneous catalysts used in organic solvent,[16] in terms of selectivity, stability and activity.

The origin of the higher activity is probably related to the limited mobility of TPAP molecules within the catalyst cage filled by $scCO_2$, which prevents self-aggregation of ruthenium derivatives formed in the oxidation process. The drying power of $scCO_2$, in association with the very hydrophobic nature of the catalyst, induces fast water removal from the inner cavities of the catalyst thus affording an extremely high selectivity for aldehyde (or ketone) production.

The kinetic analysis of the system reveals that an ester-type intermediate (RCH_2-O-Ru(OH)O_3^-), similar to that proposed for Cr(VI) alcohol oxidation, is involved in the catalytic process. Furthermore, the peculiar effect of oxygen pressure suggests that the role of the terminal oxidant is not to simply reoxidise the reduced form of the Ru catalyst but, on the contrary, rather to dehydrogenate the alcohol coordinated to the metal. The primary KIE eventually indicates that dehydrogenation is the rate-limiting step of the overall process.

The recognition of the main parameters governing the oxidative process is of paramount importance for further improvements which will be reached by appropriate modifications of the chemical-physical factors which have been elucidated in this study. Among these parameters, the possibility of further increasing TPAP segregation must be duly considered in the design of new, more durable, Ru-based sol-gel catalysts[25] for industrial aerobic oxidations in $scCO_2$.

Experimental Section

Materials

1-*D*-Benzyl alcohol was prepared from benzaldehyde by reduction with $NaBD_4$ in refluxing ether and purified by chromatography (silica gel, CH_2Cl_2). Methyl benzyl ether was prepared from benzyl alcohol by methylation with methyl iodide in the presence of KOH in dimethyl sulphoxide and purified by chromatography (silica gel, dichloromethane:hexane, 1:1). Methyltrimethoxysilane (MTMS), tetramethyl orthosilicate (TMOS), tetra-*n*-propylammonium perruthenate (TPAP), benzyl alcohol, 3-chlorobenzyl alcohol, 4-methylbenzyl alcohol, 1-methylbenzyl alcohol, 1-octanol, 2-octanol, methanol, *n*-dodecane, were purchased from Sigma-Aldrich and used without further purification. Ultra-pure water (Millipore Type 1 quality) was used in all the preparations.

Catalyst Preparation

A typical catalyst, **TP-Me3A** of batch A, obtained in the absence of NaF as polymerisation catalyst, was prepared by adding MTMS (4.90 mL) and TMOS (1.95 mL) to a solution of TPAP (55.5 mg) in MeOH (1.80 mL) cooled in an ice bath followed by the addition of H_2O (5.70 mL) under fast stirring. The sol gelled rapidly and the resulting alcogel was sealed and left to age at room temperature for 2 days prior to drying in an oven at 50 °C until reaching constant weight (5 days). The catalytic xerogel thus obtained was powdered, washed under reflux ($CH_2Cl_2 \times 2$, 40 °C) and dried at 50 °C before use.

Oxidation Procedure in $scCO_2$

The apparatus for conducting reactions in $scCO_2$ was described in detail elsewhere.[26] Catalytic oxidations of alcohols in $scCO_2$ were carried out in a 10-mL cylindrical high-pressure vessel. At the entrance and exit of the vessel were placed two 5-μM pore frits. The vessel was fitted with a magnetic bar for stirring, catalyst (5–100 mg), substrate (5 μL), and internal standard (5 μL *n*-dodecane) were charged, after which it was purged with air (for reactions performed at 0.20 bar O_2) or pure gas chromatographic-grade O_2 (for reactions performed at 1.0 bar O_2); loss of reactant and standard is negligible in the feeble stream of gases utilised, thanks to their high boiling points (216 °C for *n*-dodecane and 205 °C for benzyl alcohol). The reactor was thus sealed and placed into the SFC oven thermostatted at 75 °C. Pressurisation is achieved in about three minutes by pumping liquid carbon dioxide to the desired final pressure (22.0 MPa) while the reaction mixture was kept under stirring at 400 rpm (by means of an alternating magnetic field stirrer). Control experiments showed that a complete dissolution of alcohols and *n*-dodecane in $scCO_2$ occurs in about 10–15 min. At appropriate time intervals, reaction samples were withdrawn through the stainless steel restrictor maintained at 90 °C by means of a 6-way HPLC valve, and thus trapped in dichloromethane. The samples were analysed by GLC (Hewlett Packard 6890 system) on a 30 m EC-1000 capillary column (I.D.: 0.25 mm, thickness of film: 0.25 μM). The product concentration was measured using a previously determined response factor.

Determination of PhCDO/PhCHO Ratios

PhCDO/PhCHO ratios were determined by GC-MS analyses of various reaction mixture samples relative to the oxidation of PhCHDOH, carried out with a Hewlett-Packard 5890 gas chromatograph connected with a Hewlett-Packard 5970 mass selective detector using a 15 m SE-30 capillary column, 0.25 mm i.d. The 106 mass peak was taken as being representative of the PhCHO concentration. The 105 and 107 mass peaks, having taken into account the PhCHO contribution, are representative of the PhCDO concentration. Both 105/106 and 107/106 ratios represent a measure of the PhCDO/PhCHO ratio and therefore a measure of the hydrogen removal grade relative to deuterium.

References and Notes

[1] T. Fey, H. Fischer, S. Bachmann, K. Albert, C. Bolm, *J. Org. Chem.* **2001**, *66*, 8154.

[2] Normally, 15 to 20 kg of waste are produced along with 1 kg of useful product. For example, more than 8×10^5 tons of C_4 ketones and 2×10^6 tons of $C_1 - C_3$ aldehydes are produced annually world-wide, see also: a) J. H. Clark, *Chemistry of Waste Minimisation*, Chapman & Hall, London, **1995**; b) P. T. Anastas, M. M. Kirchhoff, *Acc. Chem. Res.* **2002**, *35*, 686.

[3] R. A. Sheldon, I. C. W. E. Arends, G. J. ten Brink, A. Dijksman, *Acc. Chem. Res.* **2002**, *35*, 774.

[4] K. Yamaguchi, N. Mizuno, *Chem. Eur. J.* **2003**, *9*, 4353.

[5] a) B. A. Steinhoff, S. S. Stahl, *Org. Lett.* **2002**, *4*, 4179; b) G. J. ten Brink, I. W. C. E. Arends, R. A. Sheldon, *Adv. Synth. Catal.* **2002**, *344*, 355.

[6] B. Betzemeier, M. Cavazzini, S. Quici, P. Knochel, *Tetrahedron Lett.* **2000**, *41*, 4343.

[7] V. B. Sharma, S. L. Jain, B. Sain, *Tetrahedron Lett.* **2003**, *44*, 383.

[8] Y. Maeda, N. Kakiuchi, S. Matsumura, T. Nishimura, T. Kawamura, S. Uemura, *J. Org. Chem.* **2002**, *67*, 6718.

[9] C. Döbler, G. M. Mehltretter, U. Sundermeier, M. Eckert, H. C. Militzer, M. Beller, *Tetrahedron Lett.* **2001**, *42*, 8447.

[10] I. E. Markó, P. R. Giles, M. Tsukasaki, I. Chelle-Regnaut, C. J. Urch, S. M. Brown, *J. Am. Chem. Soc.* **1997**, *119*, 12661.

[11] R. Lenz, S. V. Ley, *J. Chem. Soc. Perkin Trans. 1* **1997**, 3291.

[12] B. Hinzen, R. Lenz, S. V. Ley, *Synthesis* **1998**, 977.

[13] S. V. Ley, C. Ramarao, M. D. Smith, *Chem. Commun.* **2001**, 2278.

[14] For several examples, see, for instance: a) J. Blum, D. Avnir, H. Schumann, *Chemtech* **1999**, *29*, 32; b) D. Avnir, L. C. Klein, D. Levy, U. Schubert, A. B. Wojcik, "Organo-silica sol-gel materials" in: *The Chemistry of Organic Silicon Compounds*, Vol. 2, Part 3, (Eds.: Z. Rappoport, Y. Apeloig), John Wiley & Sons: New York, **1998**, pp. 2317–2362.

[15] A. Bleloch, B. F. G. Johnson, S. V. Ley, A. J. Price, D. S. Shepard, A. W. Thomas, *Chem. Commun.* **1999**, 1907.

[16] R. Ciriminna, M. Pagliaro, *Chem. Eur. J.* **2003**, *9*, 5067.

[17] a) R. Ciriminna, S. Campestrini, M. Pagliaro, *Adv. Synth. Catal.* **2003**, *345*, 1261; b) R. Ciriminna, S. Campestrini, M. Pagliaro, *Adv. Synth. Catal.* **2004**, *346*, 231; since 2002, the British chemicals manufacturer Thomas Swan & Co. operates in UK a dedicated plant for highly efficient, heterogeneous catalytic production in $scCO_2$ of a variety of valuable fine chemicals obtained with unprecedented purity grades. See also at the URL: http://www.thomas-swan.co.uk.

[18] W. P. Griffith, *Chem. Soc. Rev.* **1992**, 179.

[19] D. G. Lee, L. N. Congson, *Can. J. Chem.* **1990**, *68*, 1774.

[20] A. J. Bailey, W. P. Griffith, S. I. Mostafa, P. A. Sherwood, *Inorg. Chem.* **1993**, *32*, 268.

[21] D. G. Lee, Z. Wang, W. D. Chandler, *J. Org. Chem.* **1992**, *57*, 3276.

[22] M. Hasan, M. Musawir, P. N. Davey, I. V. Kozhevnikov, *J. Mol. Catal. A* **2002**, *180*, 77.

[23] Perruthenate tethering to the inner pore's surface of a modified mesoporous silicate MCM-41 as described in ref.[15] has been shown to be an effective strategy to achieve a re-usable heterogeneous catalyst. Such a composite material provides superior catalytic performance probably thanks to the reduced possibility of forming oxidation-inactive colloidal RuO_2.

[24] a) G. Jenzer, D. Sueur, T. Mallat, A. Baiker, *Chem. Commun.* **2000**, 2247; b) G. Jenzer, T. Mallat, A. Baiker, *Catal. Lett.* **2001**, *73*, 5; c) M. Besson, P. Gallezot, *Catal. Today* **2000**, *57*, 127; d) J. D. Grunwaldt, M. Caravati, M. Ramin, A. Baiker, *Catal. Lett.* **2003**, *90*, 221.

[25] Sol-gel silica-entrapped metal catalysts are now commercially available. Recently, the British fine chemicals manufacturer Avecia licensed Johnson Matthey sol-gel technology for preparing organic-inorganic silica hybrid gels doped with chiral ligands named CTIS CACHy^{TM} (CTIS: Chiral Technologies Interface System, CACHy: Catalytic Asymmetric CyanoHydrin) which allow efficient large-scale enantioselective conversion of aldehydes and ketones into chiral cyanohydrins for the pharmaceutical industry. For a recent account on the applications of the sol-gel catalyst technology in organic chemistry, see also: R. Ciriminna, M. Pagliaro, *Curr. Org. Chem.* **2004**, *18*, 1851.

[26] S. Campestrini, U. Tonellato, *Adv. Synth. Catal.* **2001**, *343*, 819.