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The Catalytic Efficacy of Co(salen)(AL) in O_2 Oxidation Reactions in CO_2-Expanded Solvent Media: Axial Ligand Dependence and Substrate Selectivity

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Abstract This work correlates the basicity of various axial ligands (AL), including triethylamine, methylimidazole, pyridine, acetonitrile or water, with the efficacy of catalytic oxidation of 2,6-di-tert-butylphenol by Co(salen)(AL) in CO_2-expanded methylene chloride. Further, Co(salen)(AL)O_2 abstracts hydrogen atoms from substrates of high to intermediate reactivity (BDECH $\leq \sim 90$ kcal/mol).

Keywords Co(salen) · Oxygen oxidations · Cobalt catalysts · CO_2 expanded solvents

1 Introduction

Selective catalytic oxidation reactions produce multi-billion dollar polymer intermediates, pharmaceuticals and various consumer products, and, among others, agrichemicals [1]. Dioxygen is the preferred oxidant and use requires activation via transition metal catalysts [2] in order for it to accomplish the selective transformation of the substrate to products. The cobalt oxygen carriers [3] are an important class of catalysts that both reversibly bind and activate the oxygen molecule. Tetradentate Schiff base catalysts like Co(salen) are known to bind oxygen most effectively when a so-called axial ligand, AL, also binds to the cobalt producing the corresponding penta-coordinate structure [4]. It is an accepted fact that the binding of a ligand in the axial position of alters the electronic structure of the metal center and influences the binding/activation of an O_2 molecule bound at the opposite *trans* position [2–4]. This is rationalized on the basis of the structural evidence that the bound O_2 moiety most closely resembles the superoxide ion, O_2^-. In turn, this result indicates that the binding of O_2 to cobalt(II) involves the donation of electron density to the bound O_2, a process that should be promoted by the presence of a good electron donor *tran*s to the O_2 [3]. Previous mechanistic studies of the oxidation of phenolic substrates has provided qualitative support for the significance of the axial ligand in this catalytic cycle [5].

The work reported here involves a systematic study of the activity of Co(salen)/O_2 reaction system as a function of structural changes in its ligand components and the evaluation of the selectivity and potential utility of Co(salen)/O_2 systems in oxidation catalysis. The use of CO_2-expanded solvents (CXLs) builds on previous studies in these labs that have established CXLs as optimal media for certain O_2 oxidations, including those of phenols with cobalt oxygen carriers [6a]. Improved oxygen solubility [7], tunable properties, such as solubilities of solids, diffusivity, and polarity of the reaction medium, and the wide range of suitable organic solvents that can be partnered with CO_2 [8], make CXLs an ideal choice for reactions of this kind. The enhanced O_2 availability in CXLs permits the evaluation of intrinsic catalyst activities under conditions wherein O_2 starvation is either eliminated or significantly mitigated.

In this work we seek to experimentally determine how the basicity of the axial ligand can affect the catalyst activity. The oxidation of 2,6-di-tert-butyl phenol was chosen as the model reaction system and five axial ligands were selected for the study: methylimidazole, pyridine, water, acetonitrile, triethylamine. The turnover number (moles of substrate reacted per mole of catalyst) is used as

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an indicator of catalyst activity, and CO_2-expanded methylene chloride, the reaction medium to provide a non-coordinating environment. The literature reports that Co(salen) has been used as a catalyst for the O_2 oxidation of various substrates including cyclooctane [10], veratryl alcohol [11], *para*-substituted quinines [12], alcohols [13] and methylindole [14]. In an attempt to provide a more systematic calibration of the oxidizing power of Co(salen), catalytic O_2 oxidations were studied with a variety of substrates chosen on the basis of their BDEs. This provides an indication of the hydrogen abstracting capability of the catalytic oxidation system.

2 Experimental Details

2.1 Solvents and Materials

Deionized water, HPLC-grade acetonitrile, methylene chloride, GC-grade 1-methyl imidazole, ACS grade pyridine, triethylamine (>99.5%) and 2,6-di-*tert*-butyl phenol, *N,N′*-bis(salicylidene)1,2-cyclohexanediaminato(2-) cobalt(II), i.e., Co(salen), cyclohexane, cyclohexene, 1,4-cyclohexadiene, toluene were procured from Aldrich. Chemical Co. and used as received. Co(acacen) was prepared using literature methods [15]. Oxygen (99.5%) and coolant-grade liquid CO_2 in cylinder with a dip tube, were supplied by Airgas.

2.2 Analytical Techniques

For routine analysis and quantification of products, a HP 5890 gas chromatograph with an FID and an HP-1 column (cross-linked methyl silicone gum), 50 m in length, 0.2 mm diameter and 0.5 μm film thickness, was used. An Agilent 6890 GC-MS system with an HP1-MS was used for compound identification and verification.

2.3 Apparatus and Procedures

2.3.1 Phase Behavior Studies

The phase behavior of Co(salen) in the methylene chloride/CO_2 medium was studied at 40 °C (reaction temperature) in a Jerguson™ view cell procured from Clark Reliance® Corporation. Details of the experimental setup may be found elsewhere [6a, 8]. The temperature of the cell was held constant with a water bath. The temperature and pressure of the cell were monitored using a thermocouple and a transducer respectively. A known volume (V_0) of a solution containing a fixed amount of Co(salen) in methylene chloride was added to the view cell after the cell had reached the desired temperature. CO_2 was bubbled into this mixture in a slow and intermittent manner to ensure that equilibrium was attained. The volumetric expansion ratio $[V(T, P)/V_0(P_0, T)]$ = the equilibrated volume V of the CO_2-expanded liquid phase at T and P divided by the initial volume of the neat solution at T and P_0] was recorded as a function of total cell pressure.

2.4 Oxidation Experiments

Oxidation reactions were performed in a Type 316 stainless steel hollow cylindrical view cell made by Thar® Designs. The effective reactor volume was 7.5 mL. The cell is fitted with sapphire windows at both ends, sealed with O-rings and screw caps. The body of the cell is equipped with ports to accommodate a CO_2/O_2 inlet, a sample withdrawal device, a transducer (Validyne-DP15 rated at 206 bar), a thermocouple, and a safety rupture disk (rated at 336 bar). All connections use Swagelok fittings. Temperature and pressure are monitored and controlled using the computer controlled automation tool Camile TG® (Argonaut Technologies). More details on the experimental setup may be found elsewhere [6a, 8]. A mixture of Co(salen) and 2,6-di-*tert*-butyl phenol with the axial ligand in methylene chloride is added to the cell and then CO_2 is added until the volume of the liquid phase doubles. The temperature is increased gradually along with slow and intermittent addition of CO_2. A predetermined amount of oxygen is added after the reaction temperature is attained. The addition of oxygen is taken as the start of the reaction. At the end of the desired batch reaction time, the contents of the reactor are slowly released through a solvent column placed in an ice bath. Samples from the solvent column are analyzed using a GC (HP-5890).

3 Results and Discussion

From the phase behavior measurements, it was found that the catalyst remained in solution even when the solvent mixture was volumetrically expanded by 12-fold with CO_2. Oxidation reactions were carried out at twofold expansion ($V/V_0 = 2$), corresponding to a 50% volumetric replacement of the organic solvent with CO_2. The substrate and products also remained soluble under these conditions (Fig 1).

3.1 Influence of Axial Ligands on the Catalytic Reaction

In order to determine the dependence of the catalytic oxidation reaction on the nature of the axial ligand, the

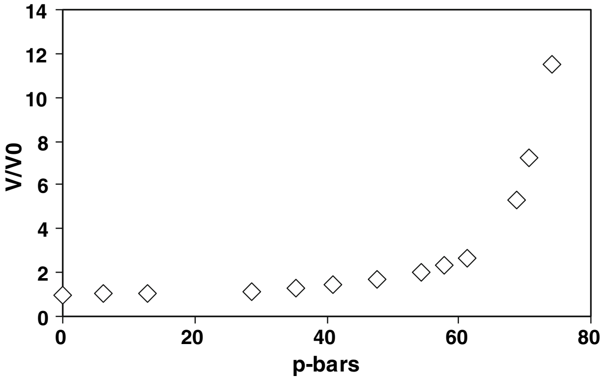

Fig. 1 Phase behavior studies: Volumetric expansion of a mixture of Co (salen) + CH_2Cl_2 with CO_2 at 40 °C; V_0: initial volume of Co (salen) + CH_2Cl_2 mixture = 3.5 mL; V/V_0 = ratio of final volume after CO_2 addition to the initial volume

oxidation was carried out with two:axial ligand:Co(salen) molar ratios, 1:1 and 10:1. These two sets of concentrations facilitate distinguishing among the axial ligands under synthetic processing conditions. Because ligands that bind very tightly will almost completely form the 1:1, 5-coordinate complex with the first equivalent of axial ligand, that is one of the ratios chosen. The second ratio would ideally drive all of the complexes to the 5-coordinate form without complication. Unfortunately, a second mole of the axial ligand (AL) can be bound and it would block the sixth binding site preventing O_2 binding and catalysis. The compromise choice is 10:1 AL:Co(salen), to drive the weaker ligands toward complete 5-coordinate complex formation. The results are plotted in Fig. 2a, b, respectively. Among the axial ligands tested, triethylamine shows the best activity at both axial ligand:catalyst ratios (1:1 and 10:1).

At low axial ligand concentrations (1:1) the turnover number (TON) decreases in the order: triethylamine $\geq$ methyl Imidazole $\gg$ pyridine $>$ acetonitrile $\sim$ water, which approximates their basicities. At high ligand concentrations (10:1), the TON decreases in the order: triethylamine $\sim$ acetonitrile $>$ pyridine $\gg$ methyl imidazole $\sim$ water. This result may be rationalized by considering relative affinities between cobalt(II) ion and the various axial ligands.

- In the case of axial ligands that bind weakly to cobalt(II), the excess is required even to bind the axial ligand to the first site on the cobalt. It is known that the 4-coordinated Co(salen) complex binds oxygen very poorly so that very little catalytic oxidation is to be expected for that species.
- Water shows about the same very low activity at both high and low water concentrations used in these experiments. The unsuccessful attempts to increase the concentration of water and therefore to produce more of its Co(salen) is tentatively attributed to the very low solubility of water in CO_2-expanded methylene chloride.

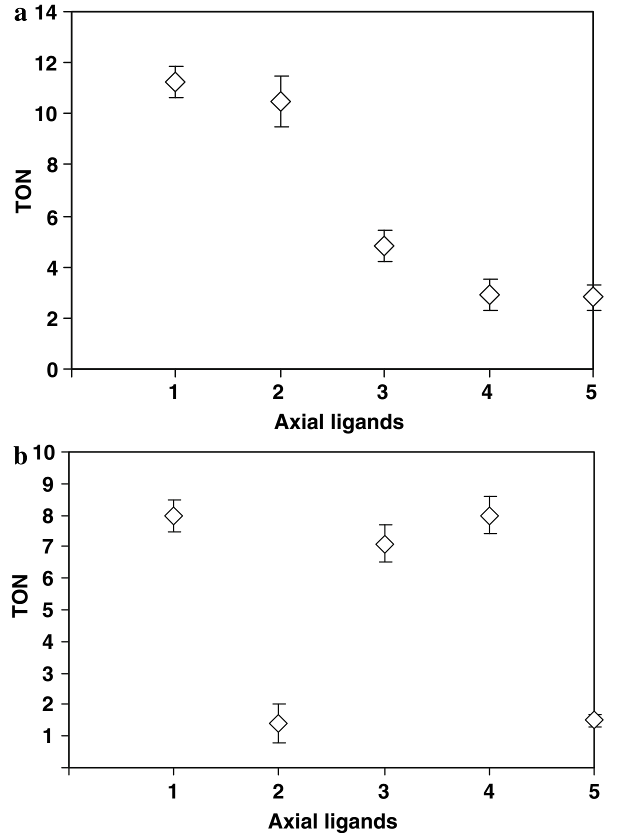

Fig. 2 (**a**) TON versus axial ligands (Co(salen):axial ligand = 1:1), 1: triethylamine; 2: methyl Imidazole; 3: pyridine; 4: acetonitrile; 5: water; Reaction conditions: cat:sub:oxidant ratio = 1:80:800; cat = 0.8 mM; solvent = CO_2-expanded methylene chloride; $V/V_0 = 2$; T = 40 °C (**b**) TON versus axial ligands (Co(salen):axial ligand = 1:10), 1: triethylamine; 2: methyl Imidazole; 3: pyridine; 4: acetonitrile; 5: water; Reaction conditions: as shown below (**a**)

- For strong binding AL like methylimidazole, no excess is required and the first molar equivalent of AL will bind to the cobalt in Co(salen), forming the 5-coordinated complex Co(salen)(AL). In this case, when the axial ligand is present in excess it can also bind to the second site of the complex leading to the formation of a 2:1 adduct, $Co(salen)(AL)_2$, that has no vacant site for oxygen binding and therefore cannot function as an oxidation catalyst.

The relative activities of triethylamine (TEA) and methylimidazole (MIM) present an interesting contrast. The two axial ligands are almost equal in activity when present at the level of one molar equivalent (Fig. 1). In contrast, the MIM derivative loses most of its catalytic activity when that axial ligand is used in excess whereas TEA retains something like 70% of its activity under the same conditions. Clearly this is because Co(salen)(MIM) is more likely to bind a second axial ligand than is Co(salen)(TEA). The data suggests that the equilibrium constants for binding of the second molecule of axial ligand would differ by a factor in the vicinity of 10. While it is clear that this small difference reflects the fact that the Lewis acidities of the cobalt(II) complexes (one bound to MIM and the other to TEA) do not have the same affinities for the second mole of base, the origin of such differences is a matter of continuous discussion. Some ascribe this difference to the reduced electron density on cobalt due to π-back bonding in the case of the MIM complex. This would make the cobalt a little more electrophilic and better able to accept the sixth ligand.16 Alternatively it may be associated with the increased polarizability, or greater softness, of MIM, which is also associated with its π-electron system. It follows that, despite the burden of its heavy steric demands, TEA produces a Co(salen) adduct that performs better than the corresponding MIM derivative in the presence of excess axial ligand. This could be a critical issue in systems where a basic medium is advantageous.

A remaining issue is the very close similarity in catalytic activities suggested by these limited studies for the entire set of axial ligands, TEA, MIM, pyridine, and acetonitrile. It must be recognized that the large excess of axial base amounts to creation of a mixed solvent so that other issues in addition to ligand binding and catalyst activation almost certainly are involved. The effect on catalyst activity of substituents on the *para*-position of pyridine was also tested and is presented in Fig. 3. There is no substantial difference in the catalytic activity when the substituents are varied. In accord with the literature [9], the effect of substituents on the salen ligand showed negligible changes in the activity of the catalyst in both neat methylene chloride and CO_2-expanded methylene chloride. A general conclusion is that while axial ligands are critical to the O_2 binding/activation function of Co(salen) as an oxidation catalyst, the oxidative reactivity is much less sensitive to the identity of the ligand than is the affinity of the ligand for the metal ion.

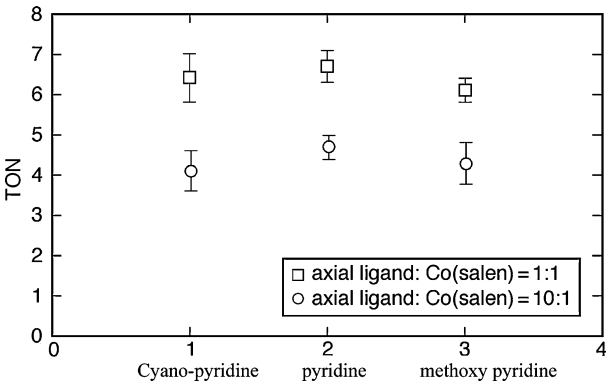

Fig. 3 TON versus axial ligands for pyridine/pyridine derivatives. Reaction conditions: as shown below Fig. 2a

3.2 Reactivity of Co(salen)

The preceding discussion concerned the dependence of catalyst activity on the axial ligand, but little attention has been given to attempts to calibrate the range of activity of this family of catalysts. Oxidation reactions, especially those involving the O_2 molecule, commonly involve formation of organic radicals by abstraction of hydrogen atoms, and that capability provides a basis for calibration [17]. Appropriately, the relative ease with which such a process can occur is evident in the strength of the carbon–hydrogen bonds (BDE, bond dissociation energy) in each potential substrate. To evaluate this aspect of the reactivity of Co(salen)/O_2 as an oxidation catalyst system, various substrates were chosen spanning a wide range of BDE values. CO_2-expanded acetonitrile was chosen as the reaction medium with MIM as the axial ligand due to its superior performance over other axial ligands in CO_2-expanded methylene chloride [6b]. The results reported in Table 1 indicate that the ability to abstract hydrogen decreases with increasing substrate C–H bond energy and that Co(salen) is active enough to oxidize substrates of intermediate reactivity in reasonable contact times. The examples in Table 1 were chosen to provide a wide range of reactive C–H bonds, beginning with the methylene hydrogens of 1,4-cyclohexadiene, then the allylic methylenes of cyclohexene before the methyl group of toluene and the hydrogens of cyclohexane. Specifically, substrates having BDE values $\leq$90 kcal/mol are suitable substrates for this catalytic oxidation system.

3.3 Reactivity of Co(acacen)

Co(acacen) is another Schiff base complex that has attracted considerable interest [17, 18] in its ability to serve as an oxygen carrier. Despite the higher O_2 binding energies reported for Co(acacen) [3b, 17, 18], it shows inferior

Table 1 Reactivity of Co(salen)

Substrate	(C–H)BDE	X(%)	Products identified with GCMS
1,4-cyclohexadiene	73	85	Benzene
Cyclohexene	82	76	Cyclohexene-ol, cyclohexene-one
Toluene	91	20	Benzaldehyde, benzoic acid
Cyclohexane	100	0	–

catalytic reactivity in comparison to Co(salen), a result that is consistent with literature reports [11]. Unlike Co(salen), Co(acacen) showed no activity in methylene chloride/CO_2 media when tested under similar conditions (see Fig 1, 2). Interest in the oxidation of substituted phenols often relates to applications for the corresponding quinones, however a second product, the 4,4′-dimer of the parent phenol often interferes with these processes. Whereas selectivity toward quinone is often high when Co(salen) is used as the catalyst, Co(acacen) was found to be a poorly selective catalyst, generating both products in equal amounts (50/50) in the temperature range 25–40 °C in neat acetonitrile/CO_2. At higher temperatures (75 °C) the dimeric diphenoquinone was formed preferentially (90% selectivity). The polarity of the solvent seems to have a substantial effect on activity of Co(acacen); increasing the solvent polarity (methylene chloride to acetonitrile) increases catalyst activity.

4 Conclusions

The effect of varying AL on the catalytic oxidation reactivity of Co(salen)(AL) was studied in the oxidation of 2,6-di-*tert*-butyl phenol. Axial ligands show a distinct effect on catalyst activity which depends on the relative concentration of the axial ligand and catalyst as well as the basicity of the axial ligand. At low concentrations the TON decreases in the sequence: TEA $\sim$ MeIm $\gg$ pyridine $>$ acetonitrile $\sim$ water.

At high ligand concentrations the TON decreases in the order TEA $\sim$ acetonitrile $>$ pyridine $\gg$ methyl imidazole $\sim$ water. Derivatives of pyridine show modest differences in the catalytic reactivity of Co(salen)(AL). The reactivity of Co(salen)(AL) has been calibrated by the ability to oxidize substrates varying in their C–H bond dissociation energies. By facile tuning of O_2 availability in the reaction phase, CXLs have proven to be suitable media to investigate subtle differences in intrinsic catalytic activity.

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References

1. Kirk-Othmer Encyclopedia of Chemical Technology (1996) Wiley, A32 140
2. (a) Holm RH (1987) Chem Rev 87:1401 (b) Sheldon RA, Kochi JK (1981) Metal catalyzed oxidations of organic compounds, Academic Press, New York, p 215 (c) Busch DH (1988) In: Oxygen complexes and oxygen activation by transition metals. Martell AE, Sawyer DT (eds) Plenum, New York, p 61 (d) Nishinaga A, Nishizawa K, Tomita H, Matsuura T (1977) J Am Chem Soc 99:1287
3. (a) Niederhoffer EC, Timmons JH, Martell AE (1984) Chem Rev 84:137 (b) Nishinaga A, Watanabe K, Matsuura T (1974) Tet Lett 14:1291 (c) Nakamoto K, Nonaka Y, Ishiguro T, Urban MW, Suzuki M, Kozuka M, Nishida Y, Kida S (1982) J Am Chem Soc 104:3386 (d) Busch DH, Alcock NW (1994) Chem Rev 94:585
4. (a) Jones RD, Summerville DA, Basolo F (1979) Chem Rev 79(2):139 (b) Drago RS, Corden BB (1980) Acc Chem Res 13:353 (c) Smith TD, PilbrowJT (1981) Coord Chem Rev 39:295 (d) McLendon G, Martell AE (1976) Coord Chem Rev 19:1 (e) Rybak-Akimova R, Otto W, Deardorf P, Roesner R Busch DH (1997) Inorg Chem 36:2746
5. (a) Zombek A, Drago RS, Corden BB, Gaul JH (1981) J Am Chem Soc 103:7580 (b) Wang X, Motekaitis RJ, Martell AE (1984) Inorg Chem 23:271 (c) Corden BB, Drago RS, Perito RP (1985) J Am Chem Soc 107:2903 (d) Bedell SA, Maretll AE (1985) J Am Chem Soc 103:7909 (e) Perito RP, Corden BJ (1988) Am Chem Soc 110:7909 (f) Sasaki I, Pujol D, Gaudemer A (1989) New J Chem 13:843 (g) Jager EG, Kanudt J, Rudolph M, Rost M (1996) Chem Ber 129:1041 (h) Tomaja DL, Vogt LH, Wirth JG (1970) J Org Chem 35:2029 (i) Musie GT, Wei M, Subramaniam B, Busch DH (2001) Inorg Chem 40(14):3336
6. (a) Wei M, Musie GT, Subramaniam B, Busch DH (2002) J Am Chem Soc 124(11):2513 (b) Wei M, Musie GT, Subramaniam B, Busch DH (2004) Green Chem 6(8):387
7. Lopez-Castillo ZK, Aki SNVK, Stadtherr MA, Brennecke JF (2006) Ind Eng Chem Res 45(15):5351
8. Musie GT, Wei M, Subramaniam B, Busch DH (1997) Inorg Chem 36:2746; Musie GT, Wei M, Subramaniam B, Busch DH (2001) Coord Chem Rev 219–221:789
9. Gust R, Ott I, Posselt D, Sommer K (2004) J Med Chem 47:5837
10. PoWtowicz JA, Pamin KA, Tabor EA, Haber J, Adamski AB, Sojka Z (2006) App Cat A 299:235
11. Kervinen K, Lahtinen P, Repo T, Svahn M, Leskelä M, Catal Tod 75 (2002) 183; Kervinen K, Korpi H, Leskelä M, Repo T (2003) J Mol Cat A 203:9
12. Joseph JB, Hames BR (1995) J Org Chem 60:2398
13. Csjernyik G, Eäll AH, Fadini L, Pugin B, Bäckvall J (2002) J Org Chem 67:1657
14. Goto M, Koyama M, Usui H, Mouri M, Mori K, Sakai T (1985) Chem Pharm Bull 33(3):927
15. Everett GW, Holm RH (1966) J Am Chem Soc 88:2442
16. Carter MJ, Rillema DP, Basolo F (1974) J Am Chem Soc 96(2):392
17. Mayer JM (1998) Acc Chem Res 31:441; Mayer JM, Mader EA, Roth JP et al (2006) J Mol Catal A Chem 251(1):24
18. (a) Carter MJ, En elhardt LM, Rillema DP, Basolo FJ (1973) Chem Soc Chem Commun 810; (b) Urban MW, Nanaka Y, Nakamoto Y (1982) Inorg Chem 21:1046; (c) Henson NJ, Hay PJ, Redondo A (1999) Inorg Chem 38:1618