

# Biphasic oxidation of arenes with oxygen catalysed by Pd(II)—heteropoly acid system: oxidative coupling versus hydroxylation

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Received 18 December 2001; received in revised form 2 January 2002; accepted 19 March 2002

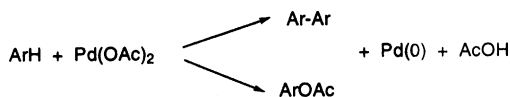
## Abstract

Liquid-phase oxidation of benzene or toluene with oxygen (100–140 °C, 5–10 atm, in AcOH–H<sub>2</sub>O) catalysed by the Pd(OAc)<sub>2</sub>–H<sub>5</sub>[PMo<sub>10</sub>V<sub>2</sub>O<sub>40</sub>] redox system leads mainly to oxidative coupling (biphenyl and terphenyl or bitolyl) and ring hydroxylation (phenol or cresol). The reaction has been carried out homogeneously (at [H<sub>2</sub>O] <15 vol.% in the solvent) and in biphasic conditions including an arene phase and an AcOH–H<sub>2</sub>O catalyst phase (at [H<sub>2</sub>O] >15 vol.%). The biphasic oxidation using AcOH–H<sub>2</sub>O 80:20 (v/v) as the solvent has been found to be more efficient towards the oxidative coupling than the homogeneous system (AcOH–H<sub>2</sub>O 95:5 (v/v)) in terms of both catalytic activity and selectivity to biaryls. Increasing the H<sub>2</sub>O/AcOH ratio in the solvent (up to AcOH–H<sub>2</sub>O 30:70 (v/v)) greatly enhances the ring hydroxylation to form phenol with 64% selectivity at 6% benzene conversion (100 °C, 5 atm O<sub>2</sub>, 2 h). © 2002 Elsevier Science B.V. All rights reserved.

**Keywords:** Palladium(II); Heteropoly acid; Benzene; Toluene; Oxidation; Oxygen; Phenol; Oxidative coupling

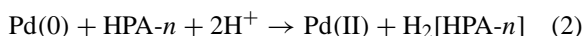
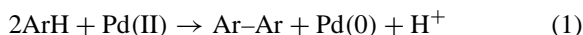
## 1. Introduction

The oxidation of arenes by Pd(II) has attracted considerable interest (for a review, see [1,2]). This reaction that is typically carried out in an AcOH solution leads to oxidative coupling (to give biaryls) and ring or side chain substitution (to form aryl or benzyl acetates) [3–6].



Strong acids (e.g. HClO<sub>4</sub>) favour the coupling, while basic additives (e.g. NaOAc) enhance the sub-

stitution [4,5]. These reactions appear to involve electrophilic substitution of arene by Pd(II) to form  $\sigma$ -arylpalladium(II) intermediate [1,2]. The oxidation can be made catalytic by reoxidising Pd(0) back to Pd(II) [1]. Oxygen can reoxidise Pd(0) directly, though at elevated temperatures and pressures (150 °C, 50 atm O<sub>2</sub> + N<sub>2</sub> (1:1)) [7]. The catalytic oxidation occurs easier when mediated by a redox co-catalyst, similarly to the Wacker-type oxidation of alkenes, the Keggin heteropoly acids of the formula H<sub>3+n</sub>[PMo<sub>12-n</sub>V<sub>n</sub>O<sub>40</sub>] (HPA-*n*, *n* ≥ 2) arguably being one of the best co-catalysts [8]. With Pd(II) + HPA-*n* as a homogeneous catalyst, the oxidative coupling of arenes proceeds as follows (70–90 °C, 1.5 atm O<sub>2</sub>) [9]:



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The Pd(II)-catalysed oxidation of benzene in aqueous media (e.g. AcOH–H<sub>2</sub>O) leads to the ring hydroxylation competing with the oxidative coupling. This offers a viable one-step route to phenol from benzene. With the Pd(II) + HPA-3 catalyst in aqueous AcOH buffered with LiOAc, benzene is oxidised with O<sub>2</sub> (60 bar, 130 °C, 4 h) to give phenol with a 70% selectivity at 15% conversion [10]. The homogeneous oxidation suffers from difficult product separation, however.

The aim of the present work is to investigate the oxidation of arenes (benzene and toluene) with O<sub>2</sub> catalysed by Pd(OAc)<sub>2</sub> + HPA-*n* in biphasic system including an arene phase and an AcOH–H<sub>2</sub>O catalyst phase. More specifically, the effect of the composition of catalyst phase on the reaction selectivity—oxidative coupling versus ring hydroxylation—is studied.

## 2. Experimental

Heteropoly acids H<sub>5</sub>[PMo<sub>10</sub>V<sub>2</sub>O<sub>40</sub>] (HPA-2) and H<sub>6</sub>[PMo<sub>9</sub>V<sub>3</sub>O<sub>40</sub>] (HPA-3) were prepared as described elsewhere [11], except converting the sodium heteropoly salts into heteropoly acids by ion exchange instead of using ether extraction. The oxidation of arenes was carried out using a Parr 4842 pressure reactor in a 125 ml PTFE-lined stainless steel reaction vessel with intense stirring. Typically, the catalyst solution (5.0 ml) contained 0.010 M Pd(OAc)<sub>2</sub> and 0.050 M HPA-2 dissolved in an AcOH–H<sub>2</sub>O solvent. To this solution was added 30 mmol (ca. 3 ml) of benzene or toluene. The reactor was pressurised with oxygen to 5.0 atm, heated to 100 °C and held at this temperature for 2 h, during which time the pressure dropped to ca. 2 atm. Then the reactor was cooled to room temperature, depressurised and opened. At this stage, as evidenced by a blue colour of the catalyst phase, HPA-2 was reduced and so was palladium. In biphasic systems, a massive black slurry of palladium metal was seen in the arene phase, which made phase separation difficult. Reaction products were extracted with a mixture of 15 ml diethyl ether and 15 ml water. The ether layer containing the products was washed with saturated NaCl aqueous solution and analysed by GC using a Varian 3380 instrument with

25 m BPX5 capillary column and FID detector. The products were identified by GC–MS using authentic samples.

## 3. Results and discussion

The oxidation of benzene or toluene with O<sub>2</sub> catalysed by the Pd(II) + HPA-*n* redox system (*n* = 2 or 3) proceeds readily in aqueous acetic acid solutions to give the coupling and hydroxylation products. From benzene, biphenyl and terphenyl (three isomers) together with phenol and biphenylol (three isomers) are the main products. From toluene, bitolyl (six isomers), cresol (three isomers), and benzaldehyde together with little benzyl alcohol, benzyl acetate and other unidentified products are obtained. Addition of water or NaOAc greatly affects the conversion and the selectivity of reaction by influencing the acidity/basicity and phase composition of the system as well as the solubility of reactants and products therein.

Initial work on the optimisation of reaction conditions led to a standard protocol that was used throughout this study. This was as follows: 0.010 M Pd(OAc)<sub>2</sub> and 0.050 M HPA-2 in 5.0 ml of AcOH–H<sub>2</sub>O solution ([H<sub>2</sub>O] = 5–70 vol.%), 30 mmol (3 ml) of benzene or toluene, 100 °C temperature, 5 atm O<sub>2</sub> pressure, and 2 h reaction time. At [H<sub>2</sub>O] < 15 vol.% in AcOH–H<sub>2</sub>O mixture, the reaction system was homogeneous, otherwise it was biphasic including an arene (upper) phase and a catalyst (bottom) phase. HPA-3 showed practically the same performance as HPA-2 did. In aqueous AcOH, HPA-2 is a strong Brønsted acid dissociating 1 to 3 protons per Keggin unit depending on [H<sub>2</sub>O] [8]. Hence the reaction medium is quite acidic unless NaOAc is added (see below).

Increasing [Pd(II)] (up to 0.05 M), the temperature (up to 140 °C), or the reaction time (up to 20 h) all led to a significant rise in arene conversion. This had, however, little effect on the reaction selectivity, except causing an increase in terphenyl yield at the expense of biphenyl in benzene oxidation, as expected. Increasing the oxygen pressure (up to 10 atm) or [HPA-2] (up to 0.25 M) caused only a slight growth in arene conversion. The former practically did not change the reaction selectivity whereas the latter caused a gradual decrease in hydroxylation selectivity because of

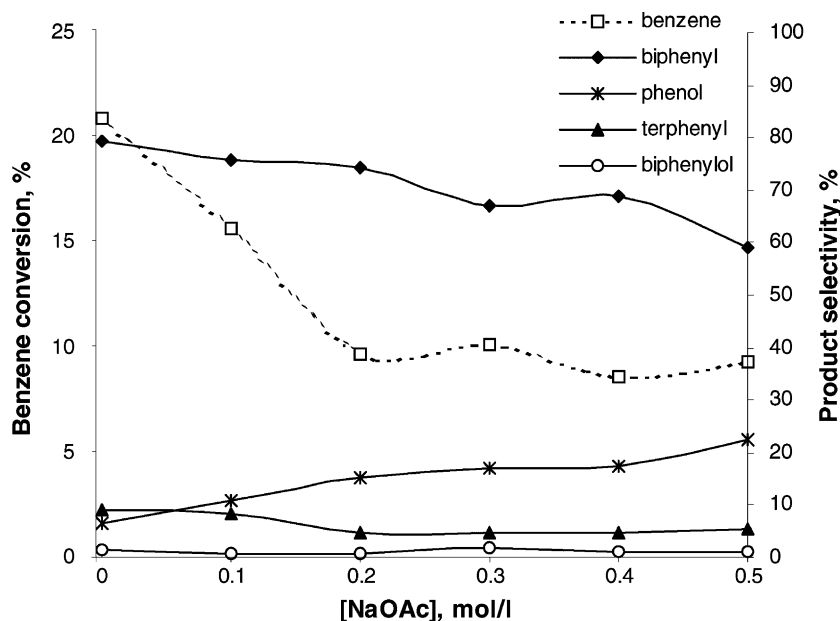
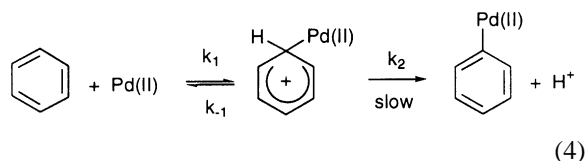


Fig. 1. Effect of additives of NaOAc on the oxidation of benzene (0.010 M Pd(OAc)<sub>2</sub>, 0.050 M HPA-2, AcOH–H<sub>2</sub>O 80:20 (v/v), 100 °C, 5 atm O<sub>2</sub>, 2 h).

an increase in the acidity of the system. These results indicate that the rate of the process is limited by step (1) and steps (2) and (3) are fast.

Figs. 1 and 2 show the effect of NaOAc additives (up to 0.5 M) on the conversion and selectivity of oxidation of benzene and toluene in AcOH–H<sub>2</sub>O 80:20 (v/v). In both cases the arene conversion decreases significantly with increasing [NaOAc], while the selectivity to hydroxylation increases at the expense of coupling. In benzene oxidation, the selectivity to phenol increases from 7 to 22%. In the case of toluene, the selectivities of both ring and side chain hydroxylation increase to give, respectively, cresols and benzaldehyde, the latter apparently being formed via benzyl alcohol.

Addition of water causes even more pronounced effect (Figs. 3 and 4). Addition of water up to 20–30 vol.% substantially increases the overall conversion of arenes as well as the selectivity to biaryls, which then go down as [H<sub>2</sub>O] increases further. This may be explained on the basis of the mechanism of electrophilic aromatic substitution by Pd(II) (Eq. (4)) [1,2], which appears to be the rate-limiting step in the oxidation process (1)–(3).



The arene palladation is known to be controlled by the slow elimination of H<sup>+</sup> from the Wheland intermediate (step  $k_2$ ), which is supported by a strong kinetic isotope effect,  $k(\text{C}_6\text{H}_6)/k(\text{C}_6\text{D}_6) = 5$  [2,4]. Addition of water to acetic acid up to certain concentration may accelerate step  $k_2$  and thus enhance reaction (4). The drop in conversion at higher [H<sub>2</sub>O] is probably caused by decreasing the solubility of arenes in the catalyst phase.

Another interesting result is that in biphasic oxidation of benzene the biphenyl/terphenyl ratio increases dramatically with the increase of [H<sub>2</sub>O]—which is an advantage of the biphasic oxidation over homogeneous oxidation.

H <sub>2</sub> O (vol.%)	5	20	30	40	50	70
Ph <sub>2</sub> /terphenyl (mol/mol)	12	13	10	19	110	110

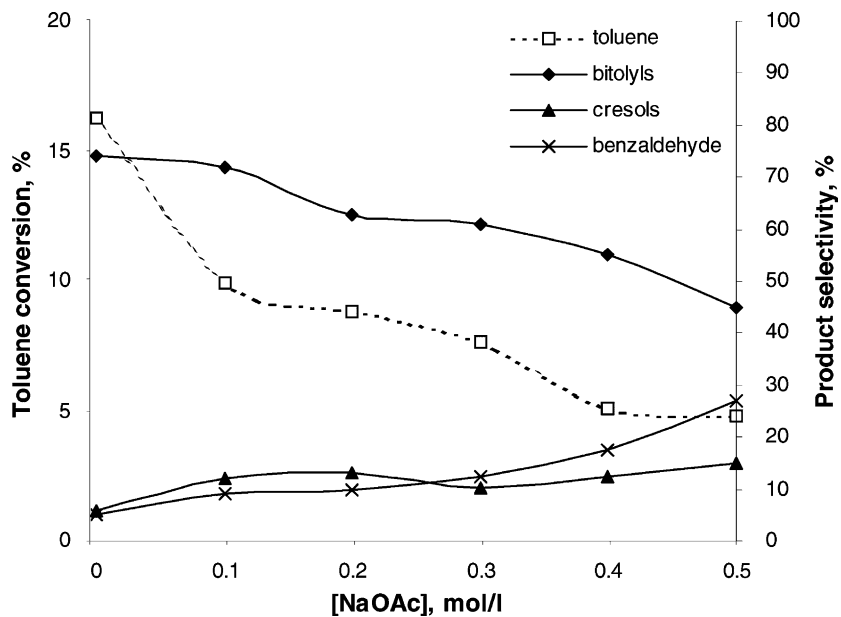


Fig. 2. Effect of additives of NaOAc on the oxidation of toluene (0.010 M Pd(OAc)<sub>2</sub>, 0.050 M HPA-2, AcOH–H<sub>2</sub>O 80:20 (v/v), 100 °C, 5 atm O<sub>2</sub>, 2 h).

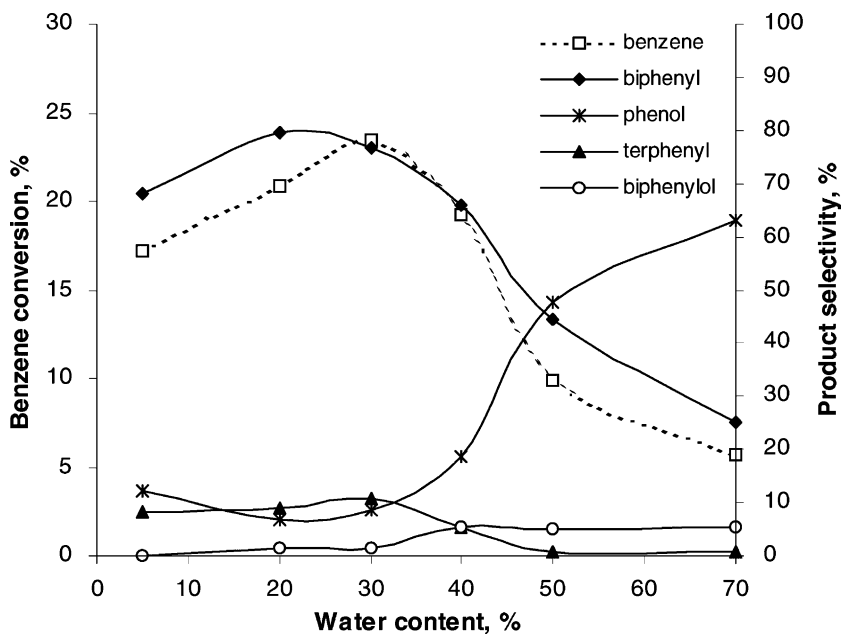


Fig. 3. Effect of water content in AcOH–H<sub>2</sub>O mixture on the oxidation of benzene (0.010 M Pd(OAc)<sub>2</sub>, 0.050 M HPA-2, 100 °C, 5 atm O<sub>2</sub>, 2 h).

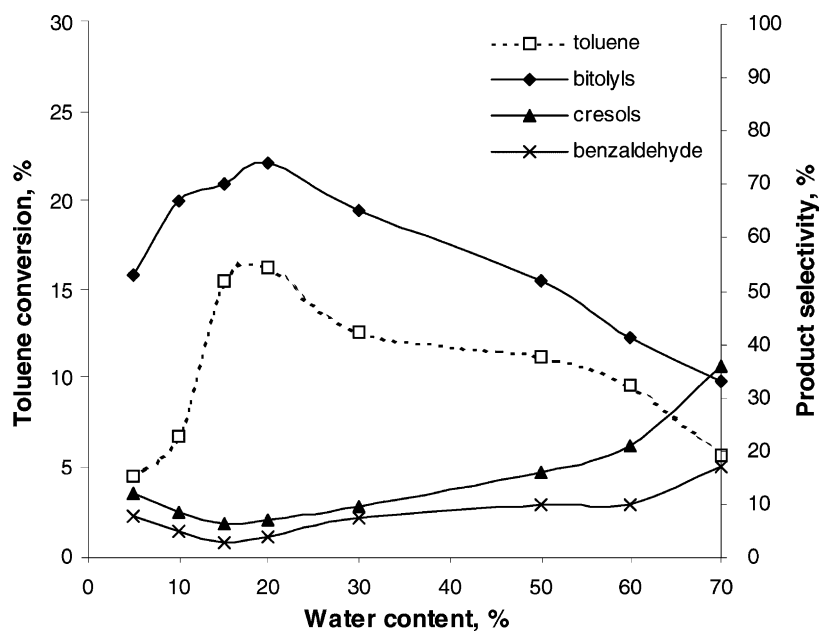


Fig. 4. Effect of water content in AcOH–H<sub>2</sub>O mixture on the oxidation of toluene (0.010 M Pd(OAc)<sub>2</sub>, 0.050 M HPA-2, 100 °C, 5 atm O<sub>2</sub>, 2 h).

Terphenyl is a product of the consecutive oxidative coupling: PhH → Ph<sub>2</sub> → terphenyl. As [H<sub>2</sub>O] increases, the solubility of biphenyl must fall faster than that of benzene, which may explain the above result.

Finally and most importantly, the addition of large amount of water greatly increases the selectivity for the oxidation of benzene to phenol, albeit decreasing the overall benzene conversion (Fig. 3). In AcOH–H<sub>2</sub>O 30:70 (v/v), the selectivity to phenol reaches 64%, at 6% conversion. Similar effect, although less pronounced, is observed for the oxidation of toluene, increasing the selectivity to cresol and benzaldehyde (Fig. 4).

#### 4. Conclusions

This study demonstrates that biphasic oxidation of arenes with O<sub>2</sub> catalysed by the Pd(II) + HPA-*n* redox system in aqueous acetic acid can be tuned by simply adding water to selectively form either biaryls (up to 74–80% biphenyl or bitolyl at 16–20% conversion) or phenol (up to 64%, at 6% benzene conversion). The

latter offers a feasible direct route from benzene to phenol. The output may be improved by further optimisation of the reaction system. The biphasic oxidation also could allow easier product separation than the homogeneous reaction. Although this has not been achieved in the present work using a batch autolave (Section 2), it is hoped that in a continuous system the separation would be much easier.

#### Acknowledgements

The authors thank the EPSRC for funding (grant GR/L58644) and Dr. M.R.H. Siddiqui for his help with the experiment.

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