

Efficient *t*-butylation of phenol using the Wells–Dawson-type molybdovanadophosphoric heteropolyacid, $H_7P_2Mo_{17}VO_{62}$, as catalyst

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Wells–Dawson heteropolyacid $H_7P_2Mo_{17}VO_{62}$ proved to be an efficient catalyst for the alkylation of phenol with *t*-butyl alcohol. Under optimized conditions, 80 °C and 4 h, $H_7P_2Mo_{17}VO_{62}$ loads as low as 0.15 mol % can be used leading to high phenol conversion. The main product, 2, 4-di-*t*-butylphenol, could be obtained in moderate selectivity.

The alkylation of phenol with *t*-butylalcohol (TBA) has been studied extensively owing to industrial interest in the production as antioxidants, ultraviolet adsorbers, heat stabilisers for polymeric materials, a variety of resins, durable surface coatings, varnishes, wire enamels, printing inks, surface-active agents, rubber chemicals, fungicides, petroleum additives, *etc.*^{1–4} It is a typical acid-catalysed reaction. Investigation of both homogeneous and heterogeneous catalysts for this Friedel–Crafts alkylation reaction resulted in different selectivities and activities based mainly on the acidity of the catalysts employed. The known catalytic systems include Lewis acids, Brønsted acids,⁵ montmorillonite,⁶ metal oxide,^{7–8} an aluminum salt catalyst,⁹ cation-exchange resin,^{10,11} zeolites,^{1–2} molecular sieves,⁶ supercritical or near-critical water³ and ionic liquids.¹² Although cation-exchange resin catalysts have some advantages over other catalysts such as no equipment corrosion and no pollution of the environment, they still possess many disadvantages. Cation-exchange resin catalysts involve a tedious work-up and thus cannot be used at higher temperatures. The activity and product selectivity of cation-exchange resin catalysts are not satisfactory.^{10,11} The ionic liquid, [bmim]PF₆, can also catalyse this transformation,¹² but the active species was demonstrated to be HF, derived from the decomposition of [PF₆][–] in the presence of water.

Heteropolyacids (HPAs) have many advantages that make them economically and environmentally attractive both in academic and industrial reactions; they are useful acids and oxidation catalysts in various reactions because their catalytic features can be varied at a molecular level.^{13–15} Furthermore, Wells–Dawson heteropolyacids possess super-acidity and a remarkable stability both in solution and in the solid state.¹⁶ Additionally, Misono and coworkers demonstrated that

Wells–Dawson HPAs are suitable to adsorb polar molecules, such as alcohols, into the solid bulk. This unique behaviour called “pseudoliquid-phase behaviour” allows the reactions (both in the liquid-phase and gas-phase conditions) to take place at the surface and in the bulk of the heteropolyacid.¹⁶ Many typical acid-catalysed reactions, including tetrahydropyranation of alcohols,¹⁷ acetalisation and ketalisation,¹⁸ and etherification¹⁹ are all effective in the presence of a suitable catalyst. Recently, we have reported that $H_{6+n}P_2Mo_{18-n}V_nO_{62}$ ($n=0\sim 2,4$) has proved to be an effective catalyst for Prins cyclisation between alkenes and para-formaldehyde to produce the corresponding 1,3-dioxane derivatives.²⁰ To the best of our knowledge, there are no examples of the use of Wells–Dawson type heteropoly compounds as catalysts for this transformation. We now report an efficient catalytic alkylation reaction of phenol with TBA using a Wells–Dawson type molybdovanadophosphoric heteropolyacid as a catalyst. The influences of some important variables, such as reaction temperature, reactant ratio and the amount of the catalyst used on the activity and selectivity have been investigated.

Various heteropoly compounds were evaluated in the alkylation of phenol with TBA at 80 °C, and the results are listed in Table 1. In this liquid–solid reaction, Wells–Dawson-type heteropolyacids and molybdovanadophosphoric heteropoly compounds (Cpyr)_{*n*}H_{7–*n*}P₂Mo₁₇VO₆₂((Cpyr)_{*n*}HMVP), showed higher catalytic activity than the Keggin-type heteropolyacids. They would be expected to be stronger Brønsted acids than the Keggin-type heteropolyacids according to a simple electrostatic theory. Especially, when using $H_7P_2Mo_{17}VO_{62}$ (HMVP) as catalyst, the conversion of phenol could reach 91.2% with high selectivity to 2, 4-di-*t*-butylphenol(2,4DTBP). It is

Table 1 Effect of catalysts on the alkylation of phenol with TBA^a

Entry	Catalysts	Conversion of phenol /%	Selectivity /%			
			<i>t</i> -BPE	<i>o</i> -TBP	<i>p</i> -TBP	2,4-DTBP
1	HMVP	91.2	trace	22.4	24.6	53.0
2	P ₂ W ₁₈	52.1	31.6	32.7	16.3	19.4
3	P ₂ Mo ₁₈	49.3	24.5	23.4	42.0	10.1
4	(Cpyr) ₂ HMVP	60.9	18.6	38.0	35.2	8.2
5	(Cpyr) ₆ HMVP	41.8	20.4	40.3	36.1	3.2
6	PW ₁₂	47.6	33.7	22.7	31.2	12.4
7	PMO ₁₂	31.6	24.7	21.2	48.8	5.3
8	SiW ₁₂	39.2	27.1	21.6	42.5	9.8
9 ^b	—	0.0	0.0	0.0	0.0	0.0
10 ^c	HMVP	85.6	–	23.3	24.2	52.5

^aReaction conditions: mol ratio of phenol to TBA(20 mmol phenol), 1:3; amount of catalyst 0.03 mmol; reaction temperature, 80 °C; reaction time, 4 h.

^bIn the absence of catalyst, 10 h.

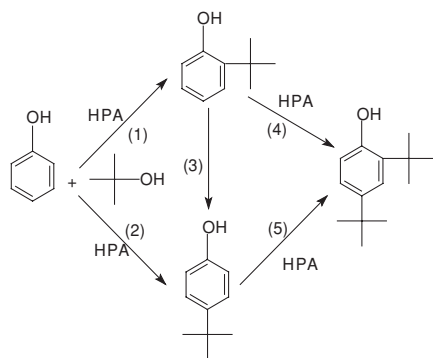
^cThree times used.

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possible that there is a unique relationship between the shape of the primary structure, the resulting secondary structures, and the remarkable influence on the catalytic activity.²¹ It is well known that Dawson-type heteropolyacids are amorphous under the reaction conditions due to the ellipsoidal shape of the polyanion, whereas Keggin-type polyanions having a spherical shape are crystalline (bcc structure).²² Owing to this difference the former can form active pseudoliquids, while the latter are much less active.²² Furthermore, by changing the constituent elements of polyanion (both hetero and addenda atoms), the acid strength of HPAs as well as the catalytic activity is able to vary in a wide range.^{22,15} It is also shown that the product selectivity was largely dependent on the acidity of the reaction system. Weakly acidic catalysts can lead to mainly oxygen alkylated products (phenylalkyl ether, *t*-BPE). The presence of the phenolic hydroxyl group (-OH) on the aromatic ring kinetically favours *o*-alkylation (*o*-isomer, e.g. *o*-TBP). However, due to steric hindrance, the thermodynamically unfavoured *o*-isomer (*o*-*t*-butylphenol, *o*-TBP) is readily isomerised into the less hindered *p*-isomer (*p*-TBP), especially under moderate acidic conditions. When strongly acidic catalysts are used, 2, 4-DTBP is predominant, and strong acidic catalysts or high reaction temperatures also produce *m*-TBP, which is formed by the secondary isomerisation of the initially formed *o*- and/or *p*-isomers. In the absence of catalyst, the reaction did not yield any product even after a prolonged reaction time (Entry 9). In the present study, alkylation of phenol with TBA over $H_7P_2Mo_{17}VO_{62}$ gave a mixture of *o*-TBP, *p*-TBP and 2, 4-DTBP. Phenyl ethers or *m*-TBP have not been detected. It is worthy of note that the result obtained over $H_7P_2Mo_{17}VO_{62}$ is much higher than those hitherto reported for this transformation.^{1-4,12} Moreover, we have found that HMVP is immiscible with reaction mixture and $H_7P_2Mo_{17}VO_{62}$ could be easily recovered by filtration. After simple treatment including washing with acetone and drying in air, the catalyst could be reused three times with slight loss of the activity (Entry 10). The following investigations of other parameters are based on HMVP as the catalyst.

The mechanism of acid-catalysis by heteropolyacids is in principle similar to the mechanism of catalysis by solutions of inorganic acids. However, heteropolyacids are capable of protonating the substrate and activating it for subsequent chemical reactions more effectively than usual inorganic acids. Based on the experimental results the effect of acid strength on the reaction scheme is proposed for the *t*-butylation of phenol over heteropoly compounds to be as in Scheme 1.

The reaction of *t*-butylation of phenol can be catalysed by Brønsted and Lewis acid sites.²¹ The Brønsted acid sites of the heteropoly compounds interact strongly with the aromatic ring of the adsorbed phenol, thus bringing it closer to the surface and permitting *t*-butylation in the *ortho* and *para*-positions (1,2). Brønsted acid sites with moderate acidity



Scheme 1

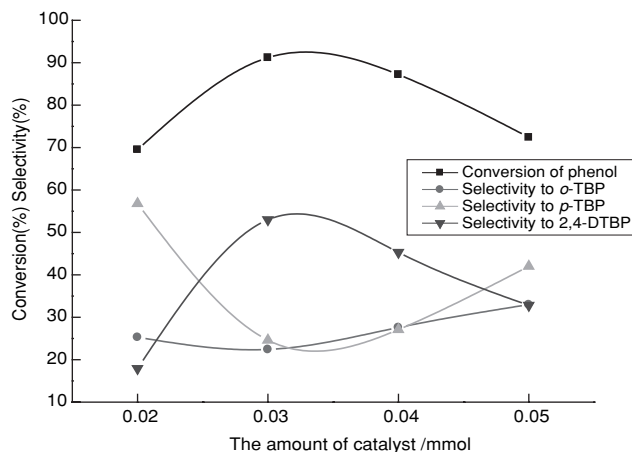


Fig. 1 Phenol conversion and product selectivity versus amount of catalyst. Conditions: mol ratio of phenol to TBA, 1:3; temperature, 80 °C; reaction time 4 h.

could promote the isomerisation of *o*-TBP to *p*-TBP over the heteropoly compounds (3). For the same reason (*ortho* effect), *o*-TBP could react with TBA to form 2,4-DTBP over strong Brønsted acid sites (4), while *p*-TBP could perform the same reaction over strong Brønsted acid sites to produce 2, 4-DTBP (5).

Figure 1 shows the effect of amount of catalyst on the reaction using $H_7P_2Mo_{17}VO_{62}$ as the catalyst. With an increase in the proportion of the catalyst from 0.02 mmol to 0.05 mmol, the conversion of phenol and selectivity for 2, 4-DTBP passed through a maximum and then decreased as the catalyst amount was increased. However, the selectivity to *o*-TBP decreased slightly. Interestingly, when more than 0.02 mmol of $H_7P_2Mo_{17}VO_{62}$ was used, the selectivities for *p*-TBP and *o*-TBP increased rapidly. The reason is currently under investigation, but it is most likely to be related to the stability at a high acid concentration. In general, for the best completion of the reaction and improvement of its selectivity, the suitable catalyst amount is 0.03 mmol.

Figure 2 illustrates the effect of reaction time on the alkylation of phenol with TBA over $H_7P_2Mo_{17}VO_{62}$ at 80 °C with a molar ratio of phenol to TBA of 1:3 (based on phenol). It can be seen that a 91.2% conversion of phenol was obtained in the first 4 h. When reaction time was extended, both the conversion of phenol and the selectivity to 2,4-DTBP was decreased. Thus, the suitable reaction time could be 4 h

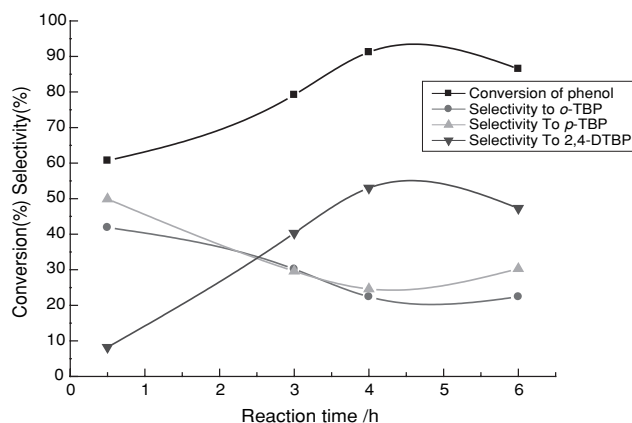


Fig. 2 Phenol conversion and product selectivity versus reaction time. Conditions: phenol: TBA (1:2) mol ratio; 80 °C, 0.03 mol $H_7P_2Mo_{17}VO_{62}$ (20 mmol phenol).

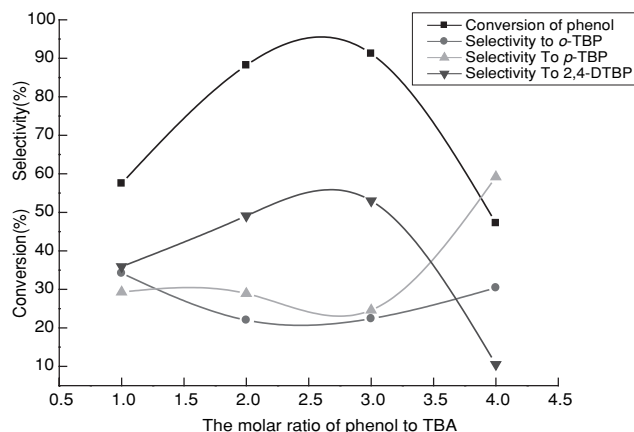


Fig. 3 Phenol conversion and product selectivity versus molar ratio of phenol to TBA. Conditions: temperature, 80 °C; time, 4 h; catalyst, 0.03 mmol (20 mmol phenol).

for the $H_7P_2Mo_{17}VO_6$ catalysed alkylation between phenol and TBA.

Figure 3 shows the results of the effect of reactant ratio on the conversion and selectivity. A series of reactions was carried out to establish the effect of reactant ratio on the conversion and selectivity under exactly the same conditions using variable amounts of TBA (20, 40, 60, 80 mmol) while keeping the amount of phenol constant at 20 mmol. The conversion of phenol and selectivity to 2,4-DTBP passed through a maximum as the amount of TBA increased, while the selectivity to *o*- and *p*-TBP passed through a minimum. The highest phenol conversion and selectivity to 2,4-DTBP was observed when the TBA concentration was three times that of phenol. At lower reactant ratios, the production of *p*-TBP is dominant and the higher ratios of TBA to phenol can enhance the selectivity to 2,4-DTBP. A higher reactant ratio is helpful in increasing the phenol conversion, too. This is probably due to the higher concentration of TBA on HPA catalyst at higher reactant ratios, which also results in preferential phenol alkylation to form 2,4-DTBP.

Figure 4 shows the effect of temperature change on the conversion of phenol in the temperature range of 50–90 °C. The conversion of phenol increased with increase in temperature from 50 to 80 °C. In contrast, when reaction temperature was above 80 °C, a slight decrease in phenol conversion was observed. Figure 4 also shows clearly that the

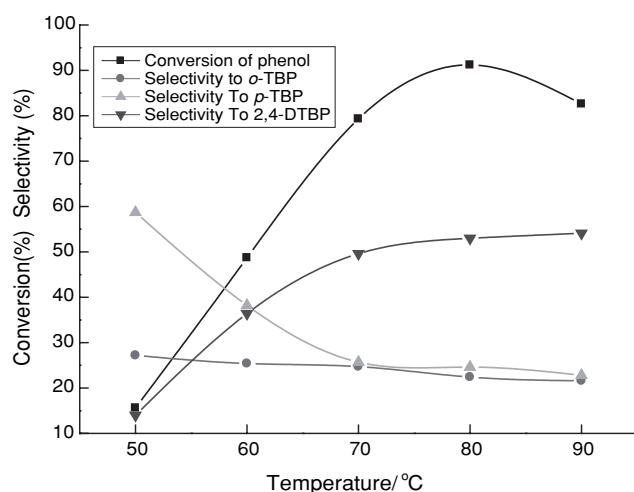


Fig. 4 Phenol conversion and product selectivity versus reaction temperature. Conditions: phenol:TBA (1:2) mol ratio; 4 h, catalyst, 0.03 mmol (20 mmol phenol).

selectivity to 2,4-DTBP reached a constant magnitude above 80 °C. As the temperature was raised from 50 to 80 °C, a decrease in the selectivity to the *o*- and *p*-TBP was observed. Therefore, the optimum reaction temperature was 80 °C. At this temperature, the selectivity to 2,4-DTBP is the highest at high phenol conversion.

In conclusion, Wells–Dawson-type heteropolyacid $H_7P_2Mo_{17}VO_6$ was used as a catalyst in the alkylation of phenol with TBA for the first time. The effects of various parameters, including reaction temperature, reaction time, molar ratio of the reactants and the amount of the catalyst, were investigated systematically. The suitable reaction conditions for this reaction were a molar ratio of 1:3 of phenol to TBA, 0.03 mmol $H_7P_2Mo_{17}VO_6$ per 20 mmol phenol, 80 °C for 4 h. Under these optimized conditions, $H_7P_2Mo_{17}VO_6$ has a potential application in the production of *t*-butylphenols with high activity and 2, 4-DTBP selectivity. Moreover, the experimental procedure is quite simple and convenient, and the reaction conditions are amenable to scale-up.

Experimental

Starting materials were obtained from Fluka company. The catalyst $H_6P_2W_{18}O_{62}$ was prepared according to previous method.²³ $H_6P_2Mo_{18}O_{62}$ was prepared according to the report of Wu.²⁴ $H_7P_2Mo_{17}VO_6$ was synthesised according to ref. [25]. $(Cpyr)_nH_{7-n}P_2Mo_{17}VO_6$ salt was precipitated by adding the desired amount of cetyl pyridinium bromide to the aqueous solution of the $H_7P_2Mo_{17}VO_6$ in a magnetically stirred flask. The $(Cpyr)_nH_{7-n}P_2Mo_{17}VO_6$ sample was obtained by evaporating the solution to dryness at 50 °C. IR spectra were recorded on Perkin-Elmer spectrometer.

All reactions were carried out in a magnetically stirred flask equipped with a small side tube for convenience of periodical sampling through a syringe. Each catalyst 0.04 mol % was added to a mixture of phenol and TBA in the reactor. This reaction mixture was then stirred at desired temperature for the appropriate time. Qualitative and quantitative analysis were conducted with a HP 6890/5973 GC/MS and a HP 1790 GC equipped with a FID detector. Products were identified by comparison of their retention times and mass spectra on GC/MS analysis with the authentic samples. The concentration of reactant and product was directly given by the system of the GC chemstation according to the area of chromatograph peak. The GC yield was obtained in Perkin-Elmer AutoSystem XL GC equipped with a SE-54 (50 m × 0.25 mm) column using nitrobenzene as internal standard.

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