Design of supramolecular metal complex catalytic systems for petrochemical and organic synthesis

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Specific features of the behavior of the supramolecular metal complex catalysts based on calixarenes, cyclodextrins, and dendrimers in the reactions of hydroformylation, Wacker oxidation, hydroxylation of aromatics, 2-naphthol coupling, and oxidative coupling of styrenes and benzene were studied. The factors affecting the catalytic activity and selectivity are discussed.

Key words: supramolecular catalytic systems, molecular imprinting, cyclodextrins, calixarenes, dendrimers, host—guest complexes, hydroformylation, Wacker oxidation, aromatics coupling, rhod-ium complexes, palladium complexes.

The control of selectivity in catalytic systems is one of the main problems in petrochemical and organic syntheses. In the recent years researchers are interested in supramolecular catalysis, the phenomena based on the use of substances capable of forming host—guest inclusion complexes with various organic compounds as components of catalytic systems. This approach provides wide possibilities for design of new highly active metal complex catalysts with high substrate, regio-, and chemiose-lectivity.¹⁻⁷

Various classes of receptor molecules, particularly, cyclodextrins, calixarenes, and dendrimers (Fig. 1), are used for the design of supramolecular catalysts.^{2-4,8,9} Cyclodextrins are macrocyclic compounds formed by α -D-glucopyranose. Calixarenes are the compounds synthesized by the condensation of phenols and aldehydes of diverse structure. The selective functionalization of the upper and lower rims of these macrocycles by heteroatomic groups can form a molecular system bearing several binding sites and in this way create catalysts capable of molecular recognition. One more type of molecular receptors is presented by dendrimers, which are polymer molecules with regular branched structures and can be considered as unique monomolecular globular micelles. Due to noncovalent interactions between several fragments of the polymer chain and an organic molecule, dendrimers can be selectively bonded to the substrate, thus enhancing the efficiency and selectivity of the immobilized metal complex catalyst.^{3,9-18} Location of the active sites at the ends of the dendrimer branches can minimize diffusional restrictions, and the dendrimers become good models for studying specific features of the behavior of the immobilized homogeneous systems.

Design of the catalysts on the basis of receptor molecules can be performed *via* two routes: (1) using the target chemical modification of the receptor acting as a ligand; (2) using the molecular imprinting method.³ The imprinting process proceeds as follows. At the first step a receptor molecule interacts with a template molecule to form a host—guest inclusion complex (Scheme 1). The structure that formed is immobilized by binding agents containing two and more functional groups. At the

Scheme 1



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Fig. 1. Macromolecular receptors for the design of the supramolecular catalysts: *a*, α - and β -cyclodextrins (*n* = 0 and 1, respectively); *b*, dendrimers; *c*, calix[*n*]arenes (*n* = 1, 3).

last step, the template is removed using diverse methods (vacuum distillation, washing with various solvents, and others).

The obtained macroligands are able to selectively form inclusion complexes with the molecules that were used as templates. Therefore, this process can be considered as a unique "tuning" of the material to a template molecule.

The purpose of the present review is to consider and analyze possibilities of using two approaches outlined above to design supramolecular catalysts for petrochemical and organic syntheses (hydroformylation, Wacker oxidation, and oxidation of aromatic compounds and oxidative aromatics coupling).

Hydroformylation of unsaturated compounds using calixarene-based catalysts

Hydroformylation of unsaturated hydrocarbons is widely used in industry for the preparation of oxygencontaining compounds. The rhodium catalytic systems including the phosphine and phosphite ligands are most active in this process. The major properties of a hydroformylation catalyst (activity, selectivity, and stability) depend substantially on the ligand nature, and its influence on the ratio and yield of the reaction products is rather complicated and determined by both electronic and steric factors.^{19–22} An increase in the steric volume of the ligand was found to increase the yield of aldehydes with the normal carbon chain, whereas the enhancement of the electron-accepting properties favors the formation of the catalytically active form of the rhodium complex due to the compensation of an excessive negative charge on the metal atom. Therefore, we synthesized the organophosphorus ligands from calix[4]- and calix[6]arenes L_1-L_7 with different electron-donating properties, macrocycle size, and orientation of the complexing groups relative to the calixarene platform.

O-Phosphorylated calixarenes L_1-L_5 (see Refs 5, 23, and 24) were synthesized by the successive interaction of the corresponding calixarenes with *n*-butyllithium and diphenylchlorophosphine (Scheme 2).

The NMR spectral data confirmed the structures of the compounds and allowed one to determine their conformational composition. The formation of a conformer mixture was avoided only in the case of the L_3 compound.







The ³¹P NMR spectrum of dipropoxycalix[4]arenephosphinite L_3 exhibits the single signal as a singlet

(δ 122.4), and the ¹H NMR spectrum contains well resolved symmetric doublets of protons of the methylene bridges at δ 3.34–4.34, indicating the rigidly fixed cone conformation.

It is known that phosphites are considerably less sensitive to oxidation in air than phosphines and phosphinites and their catalytic complexes are more stable. *p*-*tert*-Butylcalix[6]arenediphosphite L_6 and calix[6]-arenediphosphite L_7 were synthesized by the reaction of the corresponding calixarenes with phosphorus trichloride in toluene in the presence of triethylamine (Scheme 3).





 $R = Bu^{t} (L_{6}), H (L_{7})$

Mass spectrometric data (ESI) indicated that the reaction of calixarene with PCl₃ afforded dimeric compounds along with diphosphites L_6 and L_7 : the mass spectrum contains two pairs of signals with equal intensity at m/z1029, 2058 and 693, 1386 for L_6 and L_7 , respectively.



R = H, Bu^t

Pure diphosphites L_6 and L_7 were isolated by preparative column chromatography (eluent CH_2Cl_2). The L_6 macrocycle was obtained in the cone conformation.²³ In the ¹H NMR spectrum of the L₇ calixarene, the group of doublet signals of the bridging methylene protons (δ 3.52–4.78) indicates that they are nonequivalent and, hence, the macrocycle molecule is not symmetric, which is confirmed by two singlets in the ³¹P NMR spectrum (103.4 and 103.9 ppm, ¹J_{P,P} = 93 Hz). The mass spectra (ESI) of compounds L₆ and L₇ contain only the [M]⁺ signals (*m*/*z* 1029 and 693, respectively).

The NMR and mass spectrometry studies of the reactions of diphosphites L_6 and L_7 with Rh(acac)(CO)₂ and [Rh(COD)Cl]₂ (COD is cycloocta-1,5-diene) in solution at different calix/metal ratios^{8,23} show that at P/Rh = 2 (equimolar amounts of rhodium and calixarene) the rhodium atom is bound to one macrocyclic ligand. The further increase in the calixarene content in a solution (twofold and higher molar excess of cyclophane) results in the predominant formation of the RhL₂ complex in which two bulky macrocycles are coordinated to the metal center.



These data help to explain the change in the catalytic activity of the complexes based on ligands L_6 and L_7 at different P/Rh ratios (Fig. 2). The synthesized macrocycles were studied as components of the catalytic systems in the hydroformylation of unsaturated compounds of different structure. The process was carried out in a steel temperature-controlled 30-mL autoclave equipped with a magnetic stirrer at temperatures from 25 to 100 °C in a toluene solution under the synthesis gas pressure from 0.5 to 5.0 MPa. As a result, the corresponding aldehydes with the normal and branched carbon chains are formed along with some amount of the isomerization products. The rhodium complexes with the calixarene-containing ligands were synthesized in situ from Rh(acac)(CO)₂ and the corresponding calixarene. The data presented in Fig. 2 show that the yield of aldehydes decreases with an in-



Fig. 2. Dependence of the yield of aldehydes and isomeric alkenes in non-1-ene hydroformylation in the presence of the $L_6(a)$ and $L_7(b)$ ligands on the P/Rh ratio ([substrate]/[catalyst] = 150, 50 °C, 2 h, 0.5 MPa).

crease in the ratio P/Rh > 2. In our opinion, this is due to the fact that for the formation of a sterically hindered macrocomplex the access of substrate molecules and even carbon monoxide to the metal center is restricted, thus impeding the catalytic process.

Since phosphinites L_1 and L_4 were obtained as a mixture of conformers, the geometry of the complexes formed from them cannot distinctly be determined. As shown by the data in Fig. 3, the decrease in the reaction rate with an increase in the concentration of the phosphorus-containing ligand is not so pronounced as for the L_6 and L_7 ligands. In these cases, most likely, even at high P/Rh ratios, only one ligand can be coordinated to the metal center.

No formation of a complex with two macroligands was observed by the NMR study of the ligand properties of *ptert*-butyldipropoxycalix[4]arenediphosphite L₃, being in the rigidly fixed cone conformation. Unlike the singlet signal in the spectrum of the starting calixarene L₃, a doublet at δ 130 appears in the ¹³P NMR spectrum of the mixture formed upon mixing of solutions of diphosphinite L₃ and Rh(COD)₂BF₄ in CDCl₃ in a molar ratio of 2 : 1 (P/Rh = 1) (Fig. 4). The further increase in the concentration of the macrocyclic component results only in the appearance of an additional intense singlet caused by unbound phosphinite L₃. Based on the data of mass spectrometry (*m*/*z* 1311 [M - BF₄], the calculated and ob-



Fig. 3. Dependence of the yield of aldehydes and isomeric alkenes in non-1-ene hydroformylation in the presence of the $L_1(a)$ and $L_4(b)$ ligands on the P/Rh ratio ([substrate]/[catalyst] = 150, 50 °C, 2 h, 0.5 MPa).

served isotope-mass distributions virtually coincide), the structure can be proposed for the formed complex in which the rhodium atom is bonded to one cyclooctadiene fragment and two phosphorus atoms of the calixarene ligand.



Rh(COD)L₃BF₄

The complex of precisely this composition was isolated in the pure state (85% yield) upon the reaction of bis{[chloro(cycloocta-1,5-diene)]rhodium} with diphosphinitedipropoxycalix[4]arene L_3 in the presence of AgBF₄ (Scheme 4).



Fig. 4. ³¹P NMR spectra (in CDCl₃) of solutions of the L₃ ligand (*a*) and an L₃ + Rh(COD)₂BF₄ mixture at P: Rh = 1:1(*b*), 2:1(*c*), and 4:1(*d*).

Scheme 4

$$[Rh(COD)Cl]_2 + 2L_3 \xrightarrow{AgBF_4} 2Rh(COD)L_3BF_2$$

The decrease in the activity of non-1-ene hydroformylation at P/Rh > 2 was observed for the catalytic system consisting of Rh(acac)(CO)₂ and L₃ (Fig. 5). It is possible that the formation of acyl intermediate is hindered in the presence of the free macroligand preventing the coor-



Fig. 5. Dependence of the yield of aldehydes and isomeric alkenes in non-1-ene hydroformylation in the presence of the L_3 ligand on the P/Rh ratio ([substrate]/[catalyst] = 150, 50 °C, 2 h, 0.5 MPa).

Li-	Conversion	Yield of aldehydes	Regioselectivity	
gand		%		
L	42	20	70	
L2**	67	48	62	
L_3	90	74	54	
L ₄	90	75	55	
L_5	85	68	60	
L ₆	94	75	62	
L ₇	90	63	70	

* [Substrate]/[catalyst] = 150, P/Rh = 2, 50 °C, 2 h, 0.5 MPa.

** 1.0 MPa.

al center.

Table 1. Results of non-1-ene hydroformylation in the presence of the $L_1 - L_7$ ligands*

Table 3. Activity of the catalytic systems based on the L_1 and L
ligands in arylalkene hydroformylation in the absence of a solvent

Substrate	Turnover frequency of reaction/ h^{-1}		
	L_1^{b}	L_4^c	
	120	180	
	200	800	
	130	740	
ССОН	650	470	

^a [Substrate]/[catalyst] = 1000, 50 °C, 1 h, 2.5 MPa.

^b P/Rh = 4.

 c P/Rh = 3.

The rhodium complexes based on all synthesized phosphorus-containing calixarenes manifested high activity in the hydroformylation of linear alkenes (C_7-C_{12}) and several aromatic substrates.^{8,23}

dination of alkene and carbon monoxide to the met-

The data on non-1-ene hydroformylation in the presence of ligands L_1-L_7 under identical conditions are presented in Table 1. It is seen that the catalytic systems based on calix[6]arenes are characterized by the highest activity. They have larger hydrophobic cavities than calix[4]arenes.

For the hydroformylation of substituted styrenes (Table 2), the difference in sizes of the macrocyclic ligand cavity exerts virtually no effect on the reaction rate. However, the rate increases noticeably with an increase in the steric volume of the substituent in the *para*-position of the benzene ring.

Comparing the molecular models of the inclusion complexes of the catalysts based on *p*-tert-butylcalix[6]arenehexaphosphinite L_4 with arylalkenes (Fig. 6), one can suggest that the acceleration of the catalytic process is favored by an additional immobilization of the bulky substrate in the calixarene cavity, due to which the transition state of the reaction is more easily achieved. Since the solubility of *p*-tert-butylcalix[4]arenetetraphosphinite L_1 and *p*-tert-butylcalix[6]arenehexaphosphinite L_4 in aromatic compounds is high, the reactions of arylalkenes with the synthesis gas can be carried out without a solvent (the substrate to catalyst ratio reaches 1000) with high rates (Table 3), which considerably enhances the efficiency of the use of the metal complex.

The proposed phosphinite- and phosphitecalixarenes, especially the systems based on the six-membered macrocycle, can successfully be used in hydroformylation.

Oxidative coupling of aromatic compounds using cyclodextrin-based catalysts

One of the possible directions of design of the catalysts based on the molecular receptors (cyclodextrins) is the use of the molecular imprinting method.^{3,25–31} In this case, the macroligand is synthesized in the presence of a specially chosen template molecule, whose presence predetermines the direction of modification and the structure of the ligand formed.

Table 2. Activity of the catalytic systems based on the L_1 and L_4 ligands in the hydroformylation of substituted styrenes and vinylnaph-thalene*

Ligand	P:Rh	Turnover frequence of reaction/h ⁻¹						
			Me	But	MeO	Ph		
L ₁ L ₄	4 3	35 36	42 37	53 57	140 141	147 146	86 123	

* [Substrate]/[catalyst] = 150, 50 °C, 1 h, 2.5 MPa.



Fig. 6. Molecular models of the complexes of *p*-tert-butylcalix[6]arenehexaphosphinite L_4 with styrene (*a*), 2-vinylnaphthalene (*b*) and 4-vinylbiphenyl (*c*).

Molecular imprinting can be applied to the design of new catalysts using two methods. The first method is "tuning" of a catalytic system to a substrate. For this approach, we chose the reactions involving "nonrigid" molecules, *viz.*, alk-1-enes and aldehydes, as model processes. As an example we can address Wacker oxidation of alk-1-enes in the biphase systems using the palladiumand copper-containing macrocomplexes and aldehyde hydrogenation to alcohols. The biphase conditions and the ruthenium metal complexes with sulfated triphenylphosphine were used. It was shown that the catalyst activity increases considerably in the presence of the ligands synthesized by molecular imprinting. The reason may lie in the increase in the stability constants of a complex of the substrate with the macroligand.^{3,32}

The second method is performed by "tuning" to the compound, which can be considered according to its structure as an analog of the transition state of the reaction. As a result, the reaction rate can increase due to a decrease in the activation energy caused by an optimum arrangement of the macroligand fragments for the binding and mutual orientation of the reactants in the transition state. This approach seems to be the most promising for design of the catalysts for C—C bonding, in particular, the catalysts of oxidative coupling or dimerization. The reaction product, *viz.*, dimer of the corresponding aromatic compound, can be used as a model of the analog of the transition state and, hence, template.^{26,27,33–35}

The oxidative coupling of 2-naphthol and its various derivatives by iron(III) chloride under uni- and biphase conditions (Scheme 5) and the oxidative coupling of benzene with styrene and its *para*-substituted deriva-

Scheme 5



tives catalyzed by the palladium complexes were chosen as models.

The oxidative coupling of 2-naphthol and its derivatives was carried out by the action of iron trichloride under the biphase conditions (water—dichloroethane). The components of the catalytic system were the macroligands synthesized by molecular imprinting, where the template was 1,1'-bis(2-naphthol) and epichlorohydrin served as the binding agent. To estimate the influence of imprinting on the catalyst activity, we used the coefficient that reflects an increase in the reaction rate. The coefficient is defined by the TOF₁/TOF₂ ratio (TOF is turnover frequency). TOF₁ and TOF₂ is the number of moles of the product that are formed per 1 mole of the catalyst per hour when the macroligands synthesized in the presence and absence of the template are used, respectively.

For the oxidation of some 2-naphthols, the oxidative coupling rate using the macroligand synthesized by molecular imprinting is significantly higher than that for analogous compounds formed in the absence of a template molecule (Fig. 7). The arrangement of substituents in a substrate molecule during the formation of an inclusion complex with a macroligand should not prevent



Fig. 7. Coefficient of increasing the oxidative coupling rate (*K*) of 2-naphthol (*1*), 6-*tert*-butyl-2-naphthol (*2*), 2,6-dinaphthol (*3*), 1,3-naphthalenediol (*4*), and 2-naphthol-3-carboxylic acid (*5*) in the presence of the macroligand obtained by molecular imprinting (2-naphthol : FeCl₃ : macroligand = 20 : 40 : 1, water : dichloroethane = $1 : 1, 60 \circ$ C).

the C(1)–C(1') bond formation upon bringing together two molecules of the 2-naphthol derivative. Therefore, for the naphthalene derivatives with the substituents in positions 2 and 6, this increase in the rate is substantial, unlike the derivatives with the substituents in positions 1 and 3.

The results of 2-naphthol oxidation with iron trichloride in air in dichloromethane using the iron(III) complexes with β -cyclodextrin as heterogeneous catalysts are presented in Fig. 8. The best results were achieved for the macroligand synthesized by molecular imprinting and used as the component of the catalytic system. The initial activity of the complex of the macroligand synthesized in the absence of a template molecule was virtually the same as the activity of pure FeCl₃.

The iron complexes with cyclodextrins can easily be separated from the reaction products and used repeatedly.

For the cross-coupling of benzene with styrene and its *para*-substituted derivatives, *trans*-stilbene was chosen as the template during cyclodextrin modification by epichlorohydrin. The reaction was carried out in excess benzene. The heterogeneous catalyst was prepared by the interaction of palladium(II) acetate with the corresponding macroligand. The complex with the ligand synthesized using the molecular imprinting method considerably increases the yield of stilbenes for styrene and *p*-methylstyrene compared to other complexes (Fig. 9).

In the absence of a template, the hydroxy groups of cyclodextrin are substituted chaotically. Accordingly, the structure of the inclusion complexes formed with the substrate molecules prevents the reacting components from approaching in space to form the C—C bond. Moreover, the chaotically arranged groups decrease the reaction rate, if the latter is compared with the reaction rate in the presence of unsubstituted cyclodextrin.

For the bulky substrate, *viz.*, *p-tert*-butylstyrene, the rate of stilbene formation is maximum in the case of



Fig. 8. Yields of dimers in 2-naphthol oxidative coupling with the use of the heterogeneous catalysts FeCl₃ (*1*) and FeCl₃ complexes with β -cyclodextrin modified in the absence (*2*) and presence (*3*) of the template (CH₂Cl₂, 60 °C, [2-naphthol] = 0.35 mol L⁻¹, 2-naphthol : FeCl₃ : macroligand = 20 : 40 : 1).



Fig. 9. Yield of the products of the oxidative coupling of benzene with various styrenes in the presence of the heterogeneous catalyst based on β -cyclodextrin (*I*) and β -cyclodextrin modified in the absence (*2*) and presence (*3*) of the template (72 h, 100 °C, $P_{O_2} = 0.5$ MPa, benzene, [substrate] : [Pd^{II}] : [ligand] = 30 : 1 : 3, [substrate] = 0.66 mol L⁻¹).

the complex with nonmodified β -cyclodextrin. A *tert*-butylstyrene molecule is too large for the formation of a macroligand—benzene—*tert*-butylstyrene complex.

Wacker oxidation of unsaturated compounds using dendrimer-based catalysts

One of the most interesting properties of the dendrimer-based catalysts is the change in their activity with an increase in the dendrimer generation. The cases are known^{12–14} when an increase in the generation can either increase or decrease the reaction rate.

Using Wacker oxidation as an example, we were able to demonstrate that the negative dendrite effect can be used to increase the selectivity of the reaction. Polypropyleneimine dendrimers were used as macromolecules. The presence of the internal amino groups capable of coordinating one type of metals and the external active groups that bind other metals makes it possible to prepare a bimetallic catalyst with unique properties.¹⁵ Diaminobutane and diaminohexane served as the dendrimer core (Fig. 10). It is shown that, under the reaction conditions, the copper ions are bound by the dendrimer branches and are localized mainly inside the macromolecule and the palladium ions are coordinated predominantly with the nitryl groups of the dendrimer.¹⁵

Wacker oxidation was carried out in a water—ethanol (1 : 4) medium at temperatures from 60 to 90 °C in a steel autoclave under an oxygen pressure of 0.5 MPa. Linear terminal alkenes C_6-C_{12} , hept-3-ene, cyclohexene, and allylbenzene were used as substrates.

Under these conditions, the reversible isomerization of the substrate occurs rapidly in the reaction mixture (Fig. 11), and already 5 min after oct-1-ene is virtually absent in the system. A wide range of products is observed



Fig. 10. Polypropyleneimine dendrimers based on diaminobutane (a) and diaminohexane (b).

when the Wacker oxidation is carried out without a macroligand (Scheme 6).

Since the equilibrium in the alkene isomerization reaction is established very rapidly and the oxidation rate of terminal alkene is substantially higher compared to the isomers with the internal double bond, both methyl ketone and other isomeric ketones are formed in the reaction. The situation changed considerably after a den-



Fig. 11. Composition of the products of oct-1-ene isomerization 5 min after the beginning of the Wacker oxidation in the presence (*I*) and absence (*2*) of the dendrimer ($P_{O_2} = 0.5$ MPa, [Pd] : [CN] : [Cu] : [substrate] = 1 : 2 : 10 : 180).

drimer molecule was introduced into the system. The yields of ketones in the reaction with the third half-generations of dendrimers containing the diaminobutane and diaminohexane cores are given in Table 4. For all the substrates, the selectivity by methyl ketone for the use of a dendrite molecule is 1.5—4 times higher than that in the absence of the molecule. The introduction of the macromolecule exerts no effect on the rate and equilibrium of substrate isomerization, which occurs in the reaction mixture within several minutes. The difference in the yields of isomeric ketones increases in time with an increase in the temperature and substrate conversion. The selectivity increases with an increase in the dendrimer generation regardless of the nature of its core (Fig. 12).

The determining role of the dendrimer in the improvement of the process selectivity is confirmed by the data obtained when an excess of the dendrimer ligand over palladium was used. We have shown that a noticeable increase in the selectivity by methyl ketone is observed for the catalytic system with two nitryl groups per one palladium ion, whereas the selectivity by methyl ketone reaches 95% for four nitryl groups per one palladium ion.³



In the case of hept-3-ene, the addition of the dendrimer substantially decreases the yield of ketones, especially heptan-3-one and heptan-4-one. The oxidation rate decreases sharply with an increase in the dendrimer/palladium ratio. A similar effect was also observed for cyclohexene oxidation: the yield of ketone decreased 5 times. For the oxidation of allylbenzene in the absence of the dendrimer, the predominant product is ethyl phenyl ketone, which is formed, most likely, from the product of allylphenol isomerization, namely, propenylphenol. Only methyl phenyl ketone was found in the reaction products when the dendrimer was used (Table 5).



Fig. 12. Increase in the selectivity of the Wacker oxidation using the catalysts containing dendrimers $DAB(CN)_n(a)$ and $DAH(CN)_n(b)$: blank entry (1), n = 4 (2), 8 (3), and 16 (4) (80 °C, $P_{O_2} = 0.5$ MPa, [Pd] : [CN] : [Cu] : [substrate] = 1 : 2 : 10 : 180, 1 h).

The high selectivity of alk-1-ene oxidation to methyl ketone can be explained by the "negative" dendrite effect toward alkenes containing internal double bonds. The rate of their oxidation with an increase in the size of the dendrimer molecule decreases much more rapidly than the oxidation rate of terminal alkenes.

Under the reaction conditions, the dendrimer remains in the aqueous-alcohol phase and, therefore, the catalyst can completely be separated from the nonpolar products and used repeatedly without additional regeneration. To increase the volume of the nonpolar phase, an organic solvent (hexane), which with other solvents forms a biphase system, is added along with the substrate to the reaction mixture. Under these conditions, the selectivity of the process increases significantly in the reaction system (in the case of octene, from 80 to 95%) and the catalytic system can be used multiply without an activity loss (Fig. 13).



Fig. 13. Yield of ketones (*a*) and selectivity by methyl ketone (*b*) during four cycles of oct-1-ene oxidation (90 °C, $P_{O_2} = 0.5$ MPa, [Pd] : [CN] : [Cu] : [oct-1-ene] = 1 : 2 : 10 : 180, 1 h).

Substrate	<i>T</i> ∕°C	Without ligand		DAB(CN) ₁₆		DAH(CN) ₁₆	
		Y(%)	S	Y(%)	S	Y(%)	S
Hex-1-ene	60	45	3.1	27	4.7	24	6.0
Hept-1-ene	60	44	3.4	37	8.8	35	7.0
Oct-1-ene	60	32	3.7	34	8.9	25	6.5
Non-1-ene	60	30	3.9	27	8.7	23	7.2
Dec-1-ene	60	29	4.7	23	9.0	22	11.0
Dodec-1-ene	60	13	7.7	12	25.0	10	14.0
Hex-1-ene	80	74	1.8	39	3.6	23	5.3
Hept-1-ene	80	71	2.0	40	4.4	29	7.0
Oct-1-ene	80	64	2.1	44	4.5	33	7.2
Non-1-ene	80	60	2.1	57	4.6	51	7.3
Dec-1-ene	80	57	2.7	35	5.4	39	11.0
Dodec-1-ene	80	25	4.2	18	16.0	18	20.0

Table 4. Yield of ketone (Y) and selectivity by methyl ketone (S)* in the Wacker oxidation of alk-1-enes in the absence of a ligand and in the presence of the DAB(CN)₁₆ and DAH(CN)₁₆ ligands**

* *S* = [methyl ketone]/[isomeric ketones].

** $P_{O_2} = 0.5 \text{ MPa}, [Pd] : [CN] : [Cu] : [substrate] = 1 : 2 : 10 : 180, 1 \text{ h}.$

The hydroxylation of aromatics by hydrogen peroxide provides another example of the dendrimer-based catalysts. In this case, the immobilized metal complex is a unique analog of oxidation enzymes. In the latter the active centers are complexes of such metals as copper and iron, whose environment is formed by various chelate polydentate groups. To create similar centers, we modified the dendrimers of the first, second, and third generations by various aromatic aldehydes (salicylic, 2-hydroxypyridinic, and 2,4-dihydroxybenzaldehyde) (Scheme 7).

The reaction was carried out according to a standard procedure: twofold excess (based on the terminal group) of a solution of aldehyde in methanol was added to a solution of the dendrimer in methanol.⁶ The structure and purity of the synthesized compounds were confirmed

by the data of ¹H and ¹³C NMR spectroscopy and mass spectrometry.

To study the catalytic properties of the dendrimers, we used the hydroxylation of phenol and benzene by a dilute solution of hydrogen peroxide as models. The reaction was carried out under both homogeneous (water) and biphase conditions (water—dichloroethane) at 55 °C and the substrate to oxidant ratio equal to 1:1.

The major products of phenol oxidation turned out to be hydroquinone, pyrocatechol, and benzoquinone (Scheme 8), and the selectivity of the process depended substantially on the nature of the ligand and metal used. When the copper complexes were used, only pyrocatechol and benzoquinone were formed and hydroquinone was virtually absent. The latter was immediately transformed, most likely, into benzoquinone.

Substrate	Ligand	Products	Yield (%)	
Hept-3-ene	_	Heptan-2-one		
	_	Isomeric ketones	28	
	DAB(CN) ₁₆	Heptan-2-one	6	
	DAB(CN) ₁₆	Isomeric ketones	5	
Cyclohexene		Cyclohexanone	35	
	DAB(CN) ₁₆	Cyclohexanone	7	
Allylbenzene		Propenylbenzene	35	
	_	Benzyl methyl ketone	10	
	_	Ethyl phenyl ketone	50	
	DAB(CN) ₁₆	Propenylbenzene	74	
	DAB(CN) ₁₆	Benzyl methyl ketone	8	
	DAB(CN) ₁₆	Ethyl phenyl ketone	<1	

Table 5	. Results	of the V	Wacker	oxidation	of non-	terminal	alkenes*
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* $P_{O_2} = 0.5 \text{ MPa}, [Pd] : [CN] : [Cu] : [substrate] = 1 : 2 : 10 : 180, 1 h.$





Scheme 8

 $\begin{array}{c} OH \\ & \\ H_2O_2 \\ & \\ OH \\ & \\ OH \\ & \\ O \\ & \\ O \\ & \\ OH \end{array}$

It is shown that with the use of the copper complexes with the dendrimers containing the terminal amine, nitryl, and salicylamine groups the turnover number (TON) of the reaction is 1.3-2 times higher than that of the system without a ligand (Fig. 14). The most active is the system containing the DAB(NH₂)₈ dendrimer. The pronounced dendrite effect was observed for DAB(salim)_n: the hydroxylation rate increased substantially on going from the first to third generation. All the dendrimercontaining complexes (except for DAB(NH₂)_n) were



Fig. 14. Catalytic activity of the copper(II) complexes with the dendrimers of the first (1), second (2), and third (3) generations containing various terminal groups in phenol hydroxylation (55 °C, $[Cu] : [L] : [phenol] : [H_2O_2] = 1 : 2 : 80 : 80, [H_2O] : [C_2H_4Cl_2] = 5 : 1, 30 min).$ Here and in Figs 15 and 16 TON_{dend} and TON₀ are the turnover numbers of the reaction in the presence and absence of the dendrimer, respectively.

poorly dissolved in water. Under the reaction conditions, they were in the organic phase and, most likely, acted as unique phase-transfer oxidant carriers. Concentrating the catalyst in dichloroethane was confirmed by mass spectrometry, according to which almost the whole dendrimercontaining complex was in dichloroethane and its composition remained almost unchanged during the reaction.

For the use of the iron complexes under the biphase conditions, the increase in the reaction rate is somewhat lower than that in the case of the copper compounds (Fig. 15).

The results of benzene hydroxylation by hydrogen peroxide catalyzed by the copper and iron complexes with the synthesized dendrimers in a water—acetonitrile medium are presented in Fig. 16. Only the iron complexes with



Fig. 15. Catalytic activity of the iron(111) complexes with the dendrimers of the first (1), second (2), and third (3) generations containing various terminal groups in phenol hydroxylation (55 °C, [Fe] : [L] : [phenol] : $[H_2O_2] = 1 : 2 : 80 : 80$, $[H_2O] : [C_2H_4Cl_2] = 5 : 1$, 30 min).



Fig. 16. Catalytic activity of the iron complexes with the DAB(pyim)_n dendrimer of the first (1), second (2), and third (3) generations in benzene oxidation by hydrogen peroxide in an H₂O–MeCN medium (55 °C, [Fe] : [L] : [benzene] : [H₂O₂] = 1 : 2 : 80 : 160, [H₂O] : [MeCN] = 1 : 3, 30 min).

DAB(pyim)_n were active. In this case, the rate of benzene oxidation to phenol increased nearly ~ 2 times.

Thus, the presented results show that the catalysts based on the modified receptor molecules and dendrimers exhibit the high activity in the hydroformylation and Wacker oxidation of unsaturated compounds and the hydroxylation, oxidation, and oxidative coupling of aromatic compounds. These systems have advantage of having their activity and selectivity controlled using various methods. The design of the catalysts capable of molecular recognition can be one of the main directions of the development of diverse processes of petrochemical and organic synthesis.

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