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Research Article

Synthesis of 4-Methoxybiphenyl Using Pd-Containing Catalysts Based on Polymeric Matrix of Functionalized Hypercrosslinked Polystyrene

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Abstract

This paper describes synthesis of Pd-containing catalysts of Suzuki cross-coupling based on amino-functionalized hypercrosslinked polystyrene. The investigation of the influence of a palladium concentration, solvent composition, temperature, type and concentration of base, and a type of a gas phase was carried out. It was shown that the catalyst developed allows achieving conversion of 4-bromoanisole higher than 98% for less than 1 h at mild reaction conditions and in the absence of a phase transfer agent. Catalyst reduction was found to result in formation of small Pd nanoparticles (about 3 nm in diameter) and a large number of Pd clusters, which are highly active in Suzuki-Miyaura cross-coupling (conversion of 4-bromoanisole reached 90.2% for 3 h). © 2015 BCREC UNDIP. All rights reserved

Keywords: Suzuki Cross-Coupling; Palladium; Hypercrosslinked Polystyrene; Phenylboronic acid; 4-Bromoanisole

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1. Introduction

The Suzuki-Miyaura cross-coupling reaction is of great importance as it is widely used in fine organic synthesis for obtaining of active pharmaceutical ingredients, crop protection substances, and polymers. It is well known that Suzuki cross-coupling is traditionally catalyzed by homogeneous palladium complexes. However, the industrial application of the majority of developed phosphorus- or nitrogen-containing ligands is limited by their high cost [1]. Besides, a common disadvantage of homogeneous catalysts is difficulty of their separation from the reaction mixture and their reuse [2].

Thus ligandless catalytic systems are considered as an alternative to homogeneous cata-

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lysts. Pd/C, which is simple in preparation and can be easily separated from the reaction mixture, is the most well-known ligandless catalyst [2-5]. Palladium salts [1, 6] can be also attributed to the ligandless catalysts of the Suzuki reaction. The main issue with ligandless catalysts, however, is irreversible leaching of palladium and a change of particle size distribution due to an aggregation process. For example, the activity of commercial Pd/C was reported to be decreased by more than 50% at reuse [7]. To solve the problem of Pd leaching, numerous heterogeneous, heterogenized and quasi-homogeneous catalysts containing stabilized Pd complexes or nanoparticles (NPs) were developed [8-17]. It was shown that molecular forms of palladium, which form *in situ*, are the most active catalysts [7], thus, the complete prevention of the Pd leaching is impossible [18]. That is why the efforts of researchers should be aimed at the minimization of leaching. Besides, the disadvantage of many catalytic systems including polymer-stabilized Pd NPs is the necessity of addition of a phase transfer agent in order to achieve high activity in cross-coupling, especially, in the case of an aqueous medium [16, 19].

This paper is focused on the synthesis of Pd-containing catalysts based on amino-functionalized hypercrosslinked polystyrene (HPS) and the study of their catalytic properties in Suzuki cross-coupling of 4-bromoanisole (4-BrAn) and phenylboronic acid (PBA) (Figure 1). It is noteworthy that this kind of HPS has already been used for synthesis of Pd-containing Suzuki catalyst (Pd content was 3.75 wt.%) by Lyubimov *et al.* [20]. The highest conversion (99%) of 4-BrAn was achieved in aqueous medium for 5 h at 100°C while using Cs_2CO_3 as a base. The phase transfer agent (tetra-n-butylammonium bromide (TBAB)) was added to the reaction mixture. In this work we propose to improve catalytic properties of the Pd/HPS systems via changing the conditions of the catalyst synthesis and the Pd precursor nature. This allowed us to decrease the Pd content and at the same time, to increase the catalytic activity at milder reaction conditions in the absence of TBAB.

2. Materials and Methods

2.1. Materials

HPS Macronet MN100 (Purolite Int., UK) bearing amino-groups was washed with distilled water and acetone and dried under vacuum as described elsewhere [21]. A 4-Bromoanisole (4-BrAn, ≥98%) was purchased from Merck KGaA. 4-Methoxybiphenyl (4-MBP, >99%) was purchased from Tokyo Chemical Industry Co. Ltd. Phenylboronic acid (PBA, 95%), diphenylamine (99%), biphenyl (99.5%), bis(acetonitrile)palladium(II)chloride ($(CH_3CN)_2PdCl_2$, >99%), tetrahydrofuran (THF, ≥99.9%), isopropanol (*i*-PrOH, 99.5%), ethanol (EtOH, ≥99.8%), acetonitrile (99.8%), *n*-hexane (≥97%), acetone (>99.9%), potassium carbonate (K_2CO_3, ≥99%), sodium carbonate (Na_2CO_3, ≥99.5%) and sodium hydroxide (NaOH, ≥98%) were obtained from Sigma-Aldrich. All chemicals were used as received. Distilled water was purified with an Elsi-Aqua water purification system.

2.2. Synthesis of Pd/HPS Catalysts

Series of Pd-containing HPS-based catalysts was synthesized via wet-impregnation method according to the procedure described elsewhere [21]. In a typical experiment, 1 g of pretreated, dried and crushed (<63 µm) granules of MN100 were impregnated with 2.8 mL of the $(CH_3CN)_2PdCl_2$ THF solution of certain concentration. The Pd-containing polymer was dried at 70 °C, treated with 2.7 mL of Na_2CO_3 solution (concentration 0.07 mol/L) and dried until the constant weight was achieved. After that the catalyst was washed with distilled water till neutral pH and dried at 70 °C.

Thus the following catalysts were synthesized at variation of metal content: 1.5%-Pd/HPS (1.54 wt.% of Pd); 1%-Pd/HPS (0.85 wt.% of Pd) and 0.5%-Pd/HPS (0.52 wt.% of Pd). Palladium content was confirmed by the elemental analysis. Besides, for the catalyst 1.5%-Pd/HPS preliminarily reduction in hydrogen flow at 275 °C for 2 h was carried out (the catalyst was designated as 1.5%-Pd/HPS-R).

It is noteworthy that the above method of Pd/HPS catalyst synthesis assumes the use of

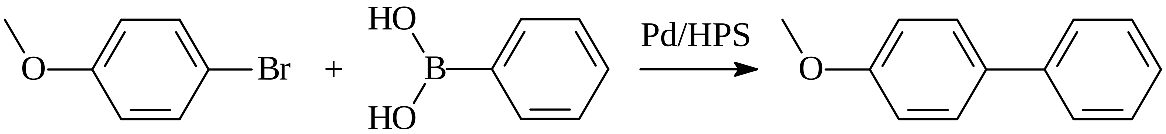

Figure 1. Scheme of Suzuki cross-coupling of 4-BrAn and PBA

organic solvent (THF) and $(CH_3CN)_2PdCl_2$ as a precursor (instead of $PdCl_2$ dissolved in water), which likely results in better distribution of Pd inside the relatively hydrophobic polymeric matrix of MN100, and may be responsible for high activity of synthesized catalysts in contrast to the procedure described by Lyubimov *et al.* [20].

2.3. Procedure of Suzuki Cross-Coupling

Testing of HPS-based catalysts was carried out in a 60 mL isothermal glass batch reactor at vigorous stirring. The total volume of liquid phase was 30 mL. The *i*-PrOH, EtOH, water and their mixtures were used as solvents. In each experiment the quantity of 4-BrAn was equal to 1 mmol, 1.5 molar excess of PBA was used. Palladium loading was varied from 0.24 mol.% up to 0.72 mol.% with respect to 4-BrAn, depending on the metal content in the catalyst. Before the catalyst addition in the reactor, in each experiment the blank test (duration of 60 min) was carried out in order to ensure that the reaction not proceeded at the absence of catalyst.

Influence of solvent composition, type of base, temperature, type of atmosphere (air, nitrogen or hydrogen), palladium loading and oxidation state (Pd(II) or Pd(0)) was studied. Samples were periodically taken and analyzed via GC-MS (Shimadzu GCMS-QP2010S) equipped with a capillary column HP-1MS (30 m × 0.25 mm i.d., 0.25 μm film thickness). Helium was used as a carrier gas at pressure of 74.8 kPa and linear velocity of 36.3 cm/s. Oven temperature was programmed: 120 °C (0 min) → 10 °C/min (160 °C) → 25 °C/min (300 °C) → 300 °C (2.4 min). Temperature of injector, interface and ion source was 260 °C, range from 10 up to 500 m/z. The concentrations of the reaction mixture components were calculated using the internal standard calibration method (diphenylamine was used as internal standard).

Table 1. SSA of HPS and Pd/HPS catalysts

Sample	SSA, m^2/g		
	Langmuir	BET	*t*-plot
HPS	839	793	189[a]; 603[b]
1.5%-Pd/HPS	858	746	148[a]; 597[b]
1.5%-Pd/HPS-R	811	721	119[a]; 603[b]
1%-Pd/HPS	869	749	120[a]; 629[b]
0.5%-Pd/HPS	868	750	150[a]; 601[b]

[a] external SSA
[b] SSA of micropores

Investigation of catalyst stability at multiple reuses was also studied for 1.5%-Pd/HPS sample (both as-synthesized and reduced). After the reaction, catalyst was filtered, washed with EtOH (30 mL), *n*-hexane (15 mL), and acetonitrile (15 mL), and then dried at 80 °C for 3 h. Catalytic activity was defined as $TOF = N_{4\text{-}BrAn} \times N_{Pd}^{-1} \times \tau^{-1} \times X$, where $N_{4\text{-}BrAn}$ and N_{Pd} are number of moles of 4-BrAn and Pd, respectively; X is conversion of 4-BrAn, and τ is the reaction time for achieving of conversion X.

2.4. Catalyst Characterization

Pd/HPS catalysts were characterized by liquid nitrogen physisorption, X-Ray Photoelectron Spectroscopy (XPS) and Transmission Electron Microscopy (TEM). Liquid nitrogen physisorption was carried out using Beckman Coulter SA 3100 (Coulter Corporation, USA). Prior to the analysis, samples were degassed in Becman Coulter SA-PREP at 120 °C in vacuum for 1 h. Weight of each sample was above 0.1 g. The following models were used for calculation of specific surface area (SSA) and pore size distribution: Langmur, Brunauer-Emmett-Teller (BET), *t*-Plot, Barrett-Joyner-Halenda (BJH). Pore size distribution was measured in the range of 3-200 nm. Microporosity was estimated using *t*-plot model. X-ray photoelectron spectroscopy (XPS) data were obtained using Mg Kα (hν = 1253.6 eV) radiation with ES-2403 spectrometer (Institute for Analytic Instrumentation of RAS, St. Petersburg, Russia) equipped with energy analyzer PHOIBOS 100-MCD5 (SPECS, Germany) and X-Ray source XR-50 (SPECS, Germany). All the data were acquired at X-ray power of 250 W. Survey spectra were recorded at an energy step of 0.5 eV with an analyzer pass energy 40 eV, and high resolution spectra were recorded at an energy step of 0.05 eV with an analyzer pass energy 7 eV. Samples were allowed to outgas for 180 min before analysis and were stable during the examination. The data analysis was performed by CasaXPS. Transmission electron microscopy (TEM) characterization was provided using a JEOL JEM1010 instrument at electron accelerating voltage of 80 kV. Samples were prepared by embedding the catalyst in epoxy resin with following microtomming at ambient temperature. Images of the resulting thin sections (*ca.* 50 nm thick) were collected with the Gatan digital camera and analyzed with the Adobe Photoshop software package and the Scion Image Processing Toolkit.

3. Results and Discussion

3.1. Characterization of Pd/HPS Catalysts

Initial HPS and Pd/HPS catalysts were characterized by the low-temperature nitrogen physisorption, XPS and TEM.

3.1.1. Low-Temperature Nitrogen Physisorption

The BET SSA of HPS after impregnation with $(CH_3CN)_2PdCl_2$ changed from 793 m^2/g to the values between 745-750 m^2/g for all the as-synthesized catalysts indicating that negligible blockage of pores took place after incorporation of the Pd compound (see Table 1). The BJH pore size distribution suggested the presence of micro-, meso- and macro-pores with predominant microporosity. After the reduction the porosity was slightly decreased to 721 m^2/g mainly due to the decrease of the fraction of meso- and macropores (from 148 m^2/g to 119 m^2/g according to the *t*-plot), while SSA of micropores changed negligibly (from 597 m^2/g to 603 m^2/g). This can be due to the predominant location of Pd NPs in mesopores of HPS.

3.1.2. X-Ray Photoelectron Spectroscopy

XPS data revealed that the surface of as-synthesized Pd/HPS catalysts contains chlorine, carbon, oxygen, nitrogen and palladium which match the combination of the Pd precursor and HPS. In the case of the catalysts examined after the use in the Suzuki reaction, the surface of samples was found to contain also sodium, boron and bromine in the quantities less than 0.6 at.%, which indicates that during the reaction the adsorption of the reaction mixture components in HPS has occurred. According to the high resolution Pd 3d spectrum, the values of the binding energy of Pd $3d_{5/2}$ in as-synthesized 1.5%-Pd/HPS are 338.6 eV (binding energy of $(CH_3CN)_2PdCl_2$ was found to be equal 338.7 eV), 337.7 eV ($PdCl_2$) [22], and 336.1 eV (small clusters of Pd) [23]. The existence of $PdCl_2$ in the catalyst can be ascribed to the removal of acetonitrile ligands in $(CH_3CN)_2PdCl_2$ due to complexation with the HPS amino groups as was also observed for hydrogenation catalysts in a previous study [24]. On the surface of the other two samples (1%-Pd/HPS and 0.5%-Pd/HPS) small amounts of Pd(0) were also found (binding energy of 335.2 eV) that can be due to the partial reduction of Pd during the catalyst synthesis (Table 2). XPS investigation was also carried out for the 1.5%-Pd/HPS sample after the repeated use in the Suzuki reaction. In the case of the unreduced catalyst, after the first use the fraction of $PdCl_2$ decreased slightly while the content of $(CH_3CN)_2PdCl_2$ drastically decreased (by a factor of 24). These changes were in line with an approximately three-fold increase of the fraction of Pd clusters. In addition, traces of Pd(0) appeared (about 0.3 at.%), which correspond to Pd NPs (see the TEM study). This observation can be explained by the specificity of the Suzuki cross-coupling catalytic cycle [7, 17] where palladium changes its oxidation state from (II) to (0) and vice versa, and small Pd clusters are responsible for catalytic activity and can result in Pd(0) NP formation. After the second use, the fraction of $PdCl_2$ in the 1.5%-Pd/HPS increased by about 5 at.%, while the fraction of palladium clusters decreased. At the same time, the increase of the Pd(0) content was observed, which can be attributed to the Pd NP formation and NP further aggregation. The examples of the high resolution Pd 3d spectra are shown in Fig. S1, the Supporting Information). In the reduced catalyst (1.5%-Pd/HPS-R) all the above mentioned forms of Pd were found. After the first use of 1.5%-Pd/HPS-R the the fraction of Pd clusters increased, which was accompanied by

Table 2. Chemical states of palladium found as a result of modelling of the Pd 3d band

Chemical state	Composition (%)						
			1.5%-Pd/HPS				
	0.5%-Pd/HPS	1%-Pd/HPS	as-synthesized	after 1st run	after 2nd run	reduced	reduced after 1st run
$(CH_3CN)_2PdCl_2$	25.0	33.4	29.2	1.2	0.7	15.1	10.9
$PdCl_2$	72.6	60.3	55.8	50.0	55.8	7.1	6.2
Pd^0	1.1	1.2	-	0.3	2.5	35.8	25.3
Clusters of Pd_n	1.3	5.1	15.0	48.5	41.0	42.0	57.6

the corresponding decrease of the fraction of both the precursor and Pd NPs (Table 2).

3.1.3. Transmission Electron Microscopy

Figure 2 shows TEM images of the 1.5%-Pd/HPS catalyst. No NPs were formed in as-synthesized 1.5%-Pd/HPS (Figure 2 (a)) that is consistent with the XPS data. It is noteworthy that small Pd clusters cannot be identified by TEM in a polymer matrix. After the first run in the Suzuki reaction the formation of Pd NPs with a mean diameter of 4.1 ± 2.2 nm was observed (Figure 2 (b)). Figure 2 (f)

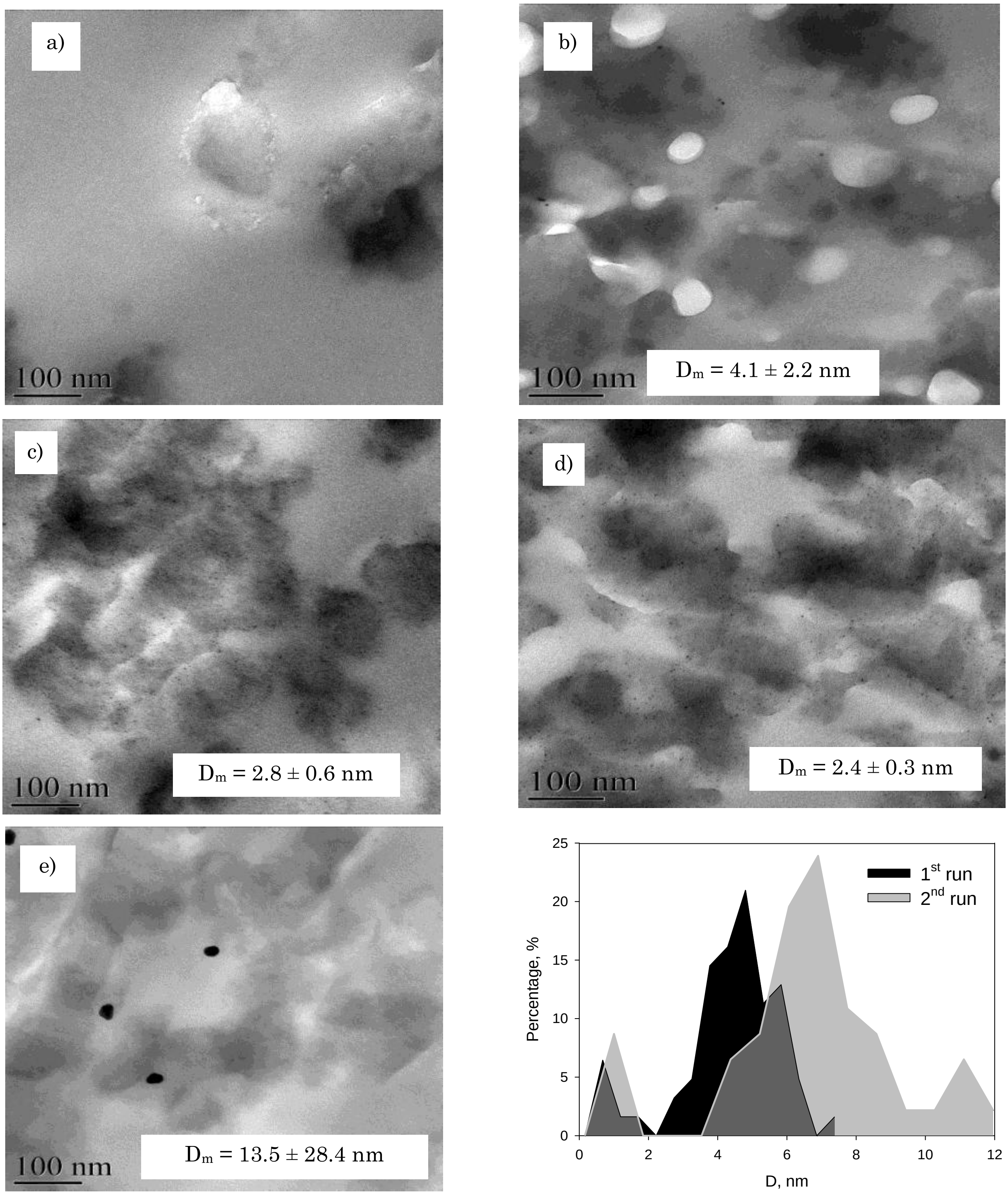

Figure 2. TEM images of 1.5%-Pd/HPS: unreduced (a); after the 1st run (b); after the prior reduction in a hydrogen flow (c); the reduced catalyst after the 1st run (d); the unreduced catalyst after the 1st run in hydrogen atmosphere (e), and histograms of particle size distributions for unreduced 1.5%-Pd/HPS after the 1st and 2nd runs in Suzuki cross-coupling

presents the comparison of the particle size distribution for the catalyst after the first and the second runs in the Suzuki reaction. It can be seen that in the case of unreduced catalyst, the increase of the Pd NP mean diameter and broadening of the particle size distribution take place during the repeated use. The TEM image of 1.5%-Pd/HPS-R is presented in Figure 2 (c). The formation of Pd NPs with a mean diameter of 2.8 ± 0.6 nm was observed and only a slight shift of the particle size distribution was detected at reuse (Figure 2 (d)). Thus, it can be concluded that mesopores of HPS are likely responsible for the Pd NP formation during the reduction in a hydrogen flow (see the data of SSA measurement). It is noteworthy that in the case of the H_2 atmosphere during the Suzuki reaction, huge NPs with mean diameter of 13.5 ± 28.4 nm were formed (Figure 2 (e)).

3.2. Catalytic Testing

3.2.1. Influence of the Pd Content

Figure 3 shows the results of testing of three as-synthesized unreduced Pd/HPS catalysts with different metal contents. The Suzuki reaction was carried at 70 °C in inert atmosphere (nitrogen) using 1.5 mmol of Na_2CO_3 as base and a mixture of EtOH and H_2O (5:1 by volume) as solvent. The highest conversion of 4-BrAn (94.7%) was achieved for as-synthesized 1.5%-Pd/HPS (Figure 3) for 55 minutes. Thus, all further experiments were carried out for this catalyst.

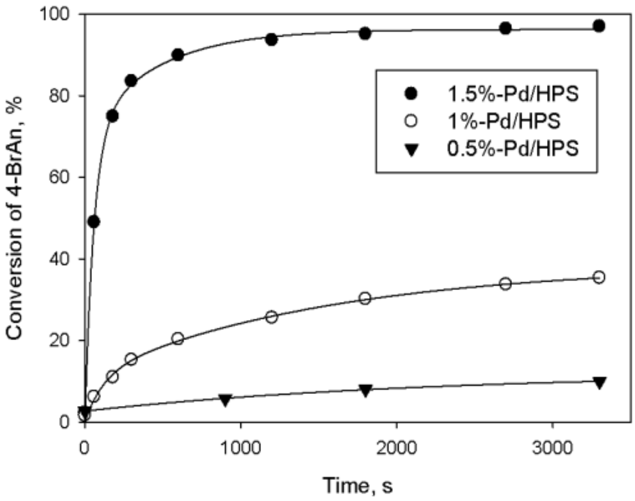

Figure 3. Dependence of the conversion of 4-BrAn on time at variations of the Pd content (nitrogen atmosphere, 70 ^{o}C, 1.5 mmol of Na_2CO_3, solvent: EtOH:H_2O = 5:1)

3.2.2. Influence of the Solvent Composition, Type of Base and the Temperature

The choice of solvent is extremely important in the Suzuki reaction. In general, a large variety of solvents is used, such as THF, dioxane, dimethyl ether, acetonitrile, N,N-dimethylformamide, low-molecular weight alcohols (methanol, EtOH, PrOH, butanol, etc.), water, and also mixtures of solvents [10, 11, 13, 25, 26]. Water is an environmentally friendly solvent; besides, polar solvents are preferable due to the possibility of enhancing of the catalyst stability [13]. However the rate of cross-coupling in pure water is extremely low in comparison with organic solvent-water mixtures [26, 27]. This fact can be explained by insufficient solubility of substrates in water and also by the difficulty of Pd(II) reduction that is an essential step of the Suzuki reaction mechanism. In order to achieve high activity in the case of pure solvents (water or organic solvents), the addition of phase transfer agents is necessary [16, 20]. Promising results were obtained in the case of organic solvent-water mixtures, but it is noteworthy that the choice of an optimal water content is important [26].

Thus, in this work *i*-PrOH, EtOH and their mixtures with water (see Table 3) were used in order to investigate a solvent influence. The use of pure *i*-PrOH as a solvent was found to result in lowest activity that is likely due to the insufficient solubility of PBA. The addition of water allowed increasing conversion of 4-BrAn from 1.4% up to 88.1% (#1-4, Table 3). The replacement of *i*-PrOH with EtOH having higher polarity caused a sharp increase of the reaction rate. For example, in the case of alcohol-water mixtures at the volumetric ratio of 5:1, the use of EtOH instead of *i*-PrOH allowed seven-fold increase of TOF (#9 vs. #2, Table 3). It is noteworthy that, in contrast to *i*-PrOH, the decrease of the EtOH fraction in the EtOH-water mixture below 5:1 (by volume) resulted in a corresponding decrease of the reaction rate (#6 and #13-15, Table 3), thus the ratio of 5:1 was chosen as optimal. It is also worth noting that the use of the solvent mixture allowed us to avoid a phase transfer agent.

Experiments on the variation of the type of base were carried out at 70 ^{o}C while using the EtOH-water mixture (5:1) as a solvent. The conversion of 4-BrAn was found to increase from 89.8% to 97.7% while increasing the strength of the base in the series $K_2CO_3 < Na_2CO_3 < NaOH$ (#8-10, Table 3). This can be explained by the fact that the base plays two-fold role: (1) acceleration of two rate-limiting steps (transmetallation and reductive elimination) and, at the same time, (2) limitation of the formation of unreactive anions [7]. Thus, the increase of the OH-group concentration allowed increasing the degree of the 4-BrAn conversion. However, the dependence of the rate of the Suzuki cross-coupling on the concentration of NaOH was found to have a maximum (Figure 4) corresponding to the value of 1.5 mmol, i.e., the decrease of the NaOH concentration to 1 mmol resulted in the decrease of 4-BrAn conversion to 78.4%, while the increase of NaOH concentration from 1.5 mmol to 2 mmol did not provide a further increase of the 4-BrAn conversion.

The temperature variation was carried out while using Na_2CO_3 as a base and EtOH-water mixture (5:1) as a solvent (#7, #9, #11 and #12, Table 3). Similar results in terms of the 4-BrAn conversion were obtained in the temperature range 60-75 ^oC. On the other hand, the temperature increase results in a slight decrease of a biphenyl content (the product of the PBA homo-coupling), which is typical for the Suzuki reaction [28]. The same trend was also observed in the case of the NaOH use (see #6 and #8, Table 3). The temperature effect can be explained by the influence on the equilibrium between different forms of Pd participating in the reaction, i.e., the temperature decrease provides the increase of the stability of the palladium complexes in solution while the higher temperatures increase the rate of the Pd reduction and precipitation.

3.2.3. Influence of the Gas Phase Composition

The gas phase influence (air, nitrogen or hydrogen) was investigated at 60 ^oC and 1.5 mmol of NaOH in the mixture of EtOH and H_2O (5:1 by volume). From the data presented (Figure 5) it can be seen that the highest conversion of 4-BrAn (98.4%) was achieved in the nitrogen atmosphere. The use of air resulted in a slight decrease of the 4-BrAn conversion to 96.9%, while the use of the reducing atmosphere (hydrogen) led to more than three-fold decrease of the conversion (to 28.7%) in comparison with the inert atmosphere. The decrease of the rate of the Suzuki cross-coupling in the case of hydrogen, is due to the fast formation of large Pd NPs (see Figure 2 (e)), which are hardly active in the Suzuki reaction.

Table 3. Influence of the reaction temperature, solvent composition and the type of a base on the catalytic behavior of 1.5%-Pd/HPS in Suzuki cross-coupling

No	Solvent	Temperature, ^oC	Type of base [a)]	Conversion of 4-BrAn, %	Yield of 4-MBP, %	TOF, h^{-1}
1	*i*-PrOH	70	Na_2CO_3	1.4	1.4	0.5
2	*i*-PrOH / H_2O = 5 : 1	70	Na_2CO_3	56.6	52.0	20.4
3	*i*-PrOH / H_2O = 2 : 1	70	Na_2CO_3	81.2	77.1	33.7
4	*i*-PrOH / H_2O = 1 : 1	70	Na_2CO_3	88.1	83.2	41.7
5	EtOH	60	NaOH	89.2	86.2	134.3
6	EtOH / H_2O = 5 : 1	60	NaOH	98.4	93.0	148.4
7	EtOH / H_2O = 5 : 1	60	Na_2CO_3	96.0	91.9	144.8
8	EtOH / H_2O = 5 : 1	70	NaOH	97.7	94.6	147.3
9	EtOH / H_2O = 5 : 1	70	Na_2CO_3	94.7	92.2	142.7
10	EtOH / H_2O = 5 : 1	70	K_2CO_3	89.8	87.5	135.2
11	EtOH / H_2O = 5 : 1	50	Na_2CO_3	93.2	88.4	140.5
12	EtOH / H_2O = 5 : 1	75	Na_2CO_3	95.7	93.6	144.3
13	EtOH / H_2O = 2 : 1	60	NaOH	93.6	91.1	141.1
14	EtOH / H_2O = 1 : 1	60	NaOH	82.7	79.6	114.3
15	EtOH / H_2O = 1 : 2	60	NaOH	81.2	73.4	112.1

[a)] base concentration 1.5 mmol

3.2.4. Influence of the Pd Oxidation State and the Investigation of the Catalyst Stability

When the 1.5%-Pd/HPS catalyst was reduced prior to the catalytic reaction, its activity dropped by half (Table 4) in comparison with the unreduced catalyst that is in accordance with the literature data [see e.g. ref. 29]. However, the investigation of the catalyst stability in three repeated uses showed that the reduced sample is more stable than the unreduced one. In addition, in spite of the lower activity in comparison with the as-synthesized sample, the reduced catalyst revealed much higher activity (by a factor of five) in comparison with the data reported elsewhere [20] at milder reaction conditions at the absence of TBAB. The high catalytic activity of the reduced 1.5%-Pd/HPS-R catalyst can be attributed to the presence of small Pd NPs with a comparatively narrow size distribution (Figure 2 (c)) as well as to the existence of a large number of Pd clusters (Table 2). It is noteworthy that the increase of the Pd loading from 0.72 mol.% to 1.1 mol.% for 1.5%-Pd/HPS-R allowed increasing of the 4-BrAn conversion from 73.3% to 90.2% for 3 h: a promising result for the reduced ligandless catalyst working in the absence of a phase transfer agent.

4. Conclusions

Palladium-containing catalysts based on amino-functionalized HPS were shown to be promising ligandless catalysts of Suzuki cross-coupling. At mild reaction conditions and in the absence of phase transfer agents, 98.4% conversion of aryl halide was achieved for the as-synthesized (unreduced) 1.5%-Pd/HPS catalyst for 55 minutes of the reaction time. The use of

Table 4. Influence of the Pd oxidation state and the repeated use on the catalytic behavior of 1.5%-Pd/HPS in Suzuki cross-coupling (reaction time 55 min)

N of cycle	Catalyst	Pd content, wt.%	Conversion of 4-BrAn, %	Yield of 4-MBP, %	TOF, h^{-1}
1	1.5%-Pd/HPS	1.54	98.4	93.0	148.4
2		1.12	96.1	92.4	199.2
3		0.91	97.0	92.2	247.5
1	1.5%-Pd/HPS-R	1.56	52.6	51.8	78.6
2		1.45	51.2	50.6	82.0
3		1.38	50.8	50.3	85.5

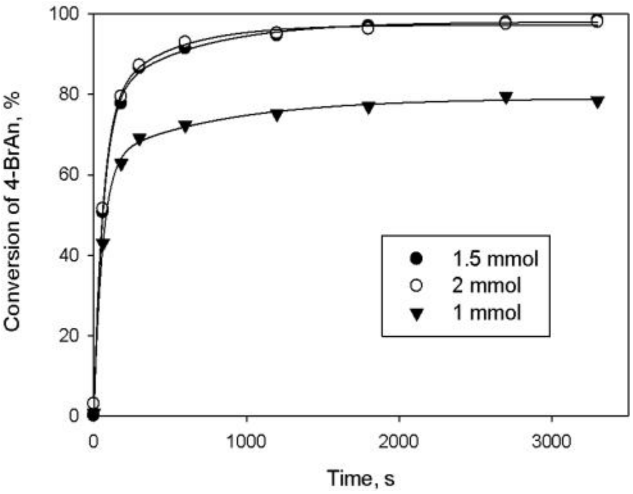

Figure 4. Dependence of the conversion of 4-BrAn on time at variations of the NaOH concentration for the 1.5%-Pd/HPS catalyst (nitrogen atmosphere, 60 °C, solvent: EtOH:H_2O = 5:1)

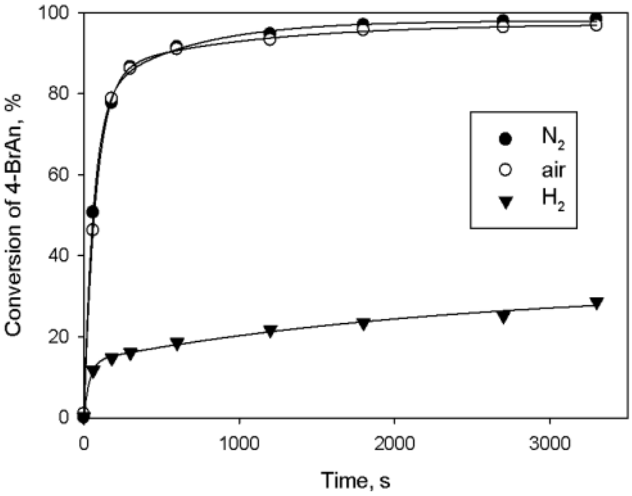

Figure 5. Dependence of the conversion of 4-BrAn on time at variations of the gas-phase composition for the 1.5%-Pd/HPS catalyst (60 °C, 1.5 mmol of NaOH, solvent: EtOH:H_2O = 5:1)

the HPS support in combination with thoroughly chosen conditions of the catalyst synthesis (type of the Pd precursor, solvent nature) allowed formation of small Pd NPs as well as of Pd_n clusters after the reduction with hydrogen, which were likely responsible for the high activity in cross-coupling of 4-BrAn and PBA. The activity of the reduced 1.5%-Pd/HPS catalyst was shown to be more than five times higher than that reported in the literature for the analogous catalytic system.

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