

Palladium-catalyzed homogeneous and heterogeneous Heck reactions in NMP and water-mixed solvents using organic, inorganic and mixed bases

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Abstract

The use of mixed solvent of *N*-methylpyrrolidone (NMP) and water and of mixed base of triethylamine and sodium carbonate was effective for promoting the rate of homogeneous Heck reaction of iodobenzene and methyl acrylate with palladium acetate as catalyst in the absence of any ligands. It was observed that palladium precipitated and formed colloidal particles during the reaction and this was promoted by the presence of water. However, the reaction proceeded with palladium species dissolved in the solvent, which were more active than those in pure NMP solvent. When the same Heck reaction was conducted with an activated carbon-supported palladium catalyst, the presence of water was also effective for promoting the rate of reaction. It was observed that palladium was leached out from the support and the dissolved palladium species were also active species for this heterogeneous reaction. The presence of water seemed to suppress the leaching of palladium into the solvent and/or enhance the formation of colloidal palladium particles. The concentration of active palladium species was smaller in the mixed solvent than in pure NMP solvent. However, these were more active, resulting in the larger rate of reaction in the presence of water. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Heck vinylation of aryl halide with olefins is one of the important methods for building up a new carbon–carbon bond and can find practical applications in the synthesis of various chemicals [1–6]. Homogeneous and heterogeneous palladium catalysts have been used for Heck reactions in a number of previous works. The rate of reaction, the product selectivity, and the

stability of catalyst are influenced by reaction conditions, of which solvent and base are important factors. They would directly participate in the formation of active palladium complexes for homogeneous reactions and affect the leaching of active palladium species (organopalladium complexes, palladium particles) from one phase to another phase for heterogeneous reactions.

Previously, we have indicated that the use of two bases, triethylamine and sodium carbonate, at the same time is effective for suppression of the dissolution of palladium from conventional carbon- and silica-supported catalysts for Heck vinylation of iodobenzene with methyl acrylate

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in *N*-methylpyrrolidone (NMP) [7]. We have also investigated the influence of different solvents in the absence and presence of triphenylphosphine ligand for the same reaction [8]. During the following course of investigation, the addition of water into an organic solvent (NMP) has been found to affect the rates of homogeneous and heterogeneous Heck reactions. The present work has been undertaken to examine the effects of the mixed base and the mixed solvent in homogeneous Heck vinylation in the absence of any ligands and in heterogeneous Heck vinylation using carbon-supported palladium catalysts. Eisenstadt [9] recently reported that the presence of water increased the solubility of an inorganic base (sodium carbonate) in NMP and it directly participated in heterogeneous Heck reactions. However, this author did not mention the dissolution of palladium into the solvent.

For practical purpose, Heck reactions should be processed in heterogeneous modes of operation for easy separation of catalyst and product and easy recycling of catalyst. Various types of heterogeneous reactions have been studied with supported catalysts [7,9–21], colloidal free particles [22–24], supported liquid film catalysts [25,26], liquid–liquid two-phase systems [27–30], high-pressure conditions [31,32] and supercritical fluids as reaction media [33–38]. The merits and demerits have presently been investigating for those heterogeneous reaction systems.

2. Experimental

All the materials, palladium acetate, 10 wt.% palladium on activated carbon, iodobenzene, methyl acrylate, NMP, triethylamine (TEA), and sodium carbonate were purchased from Wako. Homogeneous and heterogeneous Heck reactions were carried out in a 100-ml autoclave with a glass inner tube. No ligands were used in homogeneous and heterogeneous reactions and the Pd/C catalyst was reduced by flowing hydrogen at 200°C for 3 h before reactions.

Iodobenzene (5 mmol), methyl acrylate (5 mmol), and TEA were dissolved into a 30 ml solvent of NMP in the absence or presence of distilled water. Then 0.02 mmol Pd(OAc)₂ or 40 mg Pd/C catalyst and/or sodium carbonate were added to this solution. The reaction mixture was stirred at about 600 rpm and heated to the desired reaction temperature, 80°C and 110°C, for homogeneous and heterogeneous reactions, respectively. The reaction atmosphere was not controlled and the reactions were conducted under autogaseous pressures including air. After the reaction temperature was attained, a small volume of reaction mixture was sampled every 10 min and analyzed with gas chromatograph (Yanaco G3800, Silicon OV-1, 6 m) with flame ionization detector.

The concentration of Pd dissolved in the solvent was measured by atomic absorption spectroscopy. In some cases, Pd colloidal particles were formed, and they were examined by transmission electron microscopy (TEM, Hitachi H-300). A small drop of reaction mixture was placed on a TEM sample grid, dried in air, and subjected to TEM examination.

3. Results and discussion

3.1. Homogeneous reactions

Time-conversion curves are shown in Fig. 1a for homogeneous Heck reactions in mixed solvents with the mixed base. The rate of reaction is significantly promoted by using water with NMP and it is larger at higher water/NMP ratio, in accordance with the report of Eisenstadt [9]. Under the present conditions, the two substrates and TEA are completely soluble in the mixed solvent but Na₂CO₃ is partly soluble. When TEA and Na₂CO₃ are used at the same time, the latter is mainly consumed during the Heck reaction [7]. The amount of soluble Na₂CO₃ is larger in the mixed solvent than in pure NMP, and this is one of the possible factors that can explain the rate enhancement observed.

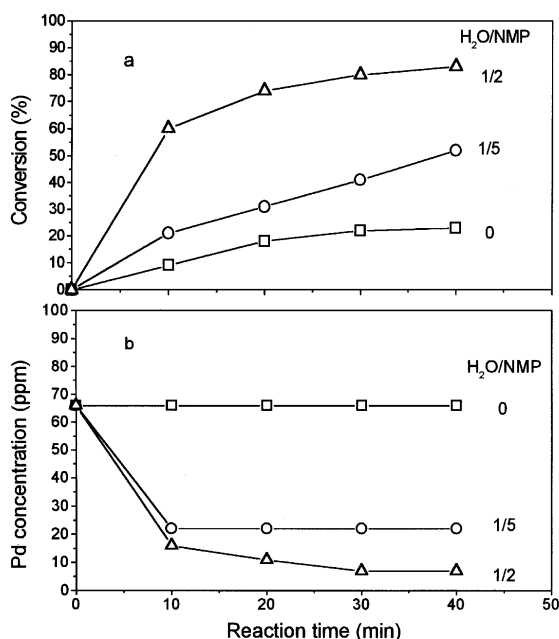


Fig. 1. Influence of water on homogeneous Heck reaction at 80°C. (a) Conversion determined from the amount of iodobenzene consumed and (b) Pd concentration in the solvent. Reaction conditions: Pd(OAc)₂ 0.02 mmol, iodobenzene and methyl acrylate 5 mmol each, TEA 1 mmol, Na₂CO₃ 2.5 mmol, solvent (NMP and/or H₂O) 30 ml.

During the above homogeneous Heck reaction, some colloidal particles were observed to form in the solution. Fig. 2a shows a TEM picture of these particles and they were indicated to be metallic Pd from electron diffraction analysis. Fig. 1b shows the change of Pd concentration in the solution during the reaction. It did not change in pure NMP while it decreased, in particular, at the first stage of reaction, in the presence of water. For pure NMP, the formation of such Pd particles were not observed (see Table 1). Thus, the addition of water caused the precipitation of Pd producing the colloidal Pd particles. After the Pd concentration did not change so much at the latter stage, the rates of reaction showed only marginal increases. So, the reaction should proceed homogeneously during the whole course of reaction. In addition to the positive and negative effects (increase of solubility of Na₂CO₃ and Pd precipitation), the presence of water has another effect. The water

molecule may be involved in the formation of active Pd species with NMP solvent through a hydrogen bonding with an oxygen of an NMP molecule, affecting its nature of coordinating with Pd. In the literature [39], the role of a hydroxyl group was indicated for the formation of a transition complex with Pd and some ligands for Pd-catalyzed allylic alkylation. In our system, the rate of reaction should be determined by a balance of those positive and negative effects. Fig. 3 shows the influence of water/NMP ratio on conversions and Pd concentrations measured at 10 and 30 min. The Pd concentration simply decreases with this ratio while the conversion has a minimum at about

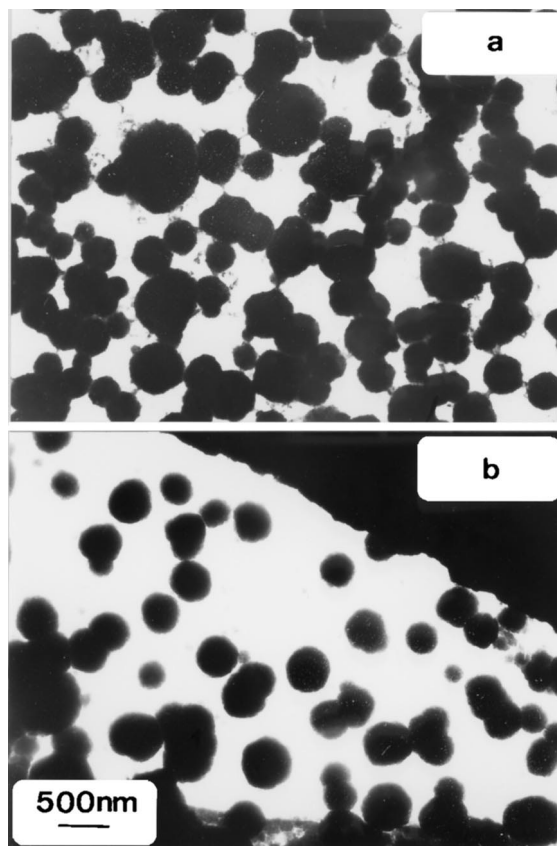


Fig. 2. Transmission electron micrographs of colloidal Pd particles formed during homogeneous (a) and (b) heterogeneous Heck reactions in the H₂O/NMP (1/2) mixed solvent using the TEA and Na₂CO₃ mixed bases. Other reaction conditions are given in Fig. 1 and Fig. 4 captions for homogeneous and heterogeneous reactions, respectively.

Table 1

Observations of formation of free palladium particles in the solvent and leaching of palladium from the surface of carbon support

Solvent	Reaction system and catalyst	
	Homogeneous ^a (palladium acetate)	Heterogeneous ^b (carbon-supported palladium)
NMP	No free Pd particles	Significant leaching of Pd into the solvent, no free Pd particles
NMP + H ₂ O	Colloidal Pd particles formed during reaction confirmed by naked eyes and TEM (Fig. 2a)	Less significant leaching of Pd into the solvent, colloidal Pd particles confirmed by TEM (similar to those of Fig. 2b)

^aReaction temperature: 80°C.

^bReaction temperature: 110°C.

0.2. When the water/NMP ratio was larger than 1, the substrates were not soluble in the mixed solvent.

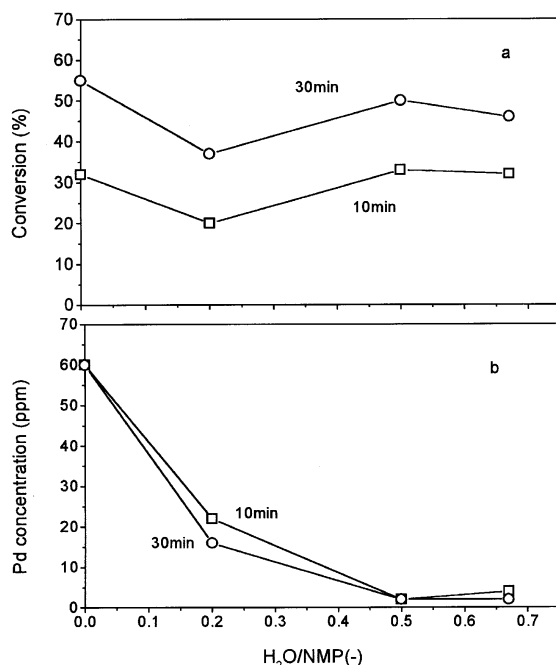


Fig. 3. Influence of water on homogeneous Heck reaction at 80°C in the presence of organic base, TEA, only. (a) Conversion determined from the amount of iodobenzene consumed, and (b) Pd concentration in the solvent. Reaction conditions: Pd(OAc)₂ 0.02 mmol, iodobenzene and methyl acrylate 5 mmol each, TEA 5 mmol, solvent (NMP and/or H₂O) 30 ml.

In Table 2, we compared the results of homogeneous Heck reactions in NMP and water/NMP (1/2) solvents with the single and mixed bases. For TEA, the addition of water did not change the rate of reaction so much, while it significantly suppressed the precipitation of Pd. For Na₂CO₃, it was almost soluble in NMP but the reaction did not take place; in the mixed solvent, the reaction occurred at a smaller rate of reaction compared with the case of TEA. The presence of Na₂CO₃ also suppressed the Pd precipitation in the water/NMP solvent and this effect seemed to be larger than that with TEA. The use of the mixed base gave higher rate of reaction and more effectively suppressed the Pd precipitation in the mixed solvent compared with the results with TEA only.

3.2. Heterogeneous reactions

Fig. 4a shows the time-conversion curves with Pd/C catalyst and the mixed base in NMP and water/NMP solvents. The use of water significantly increased the rate of reaction. During these reactions, supported Pd species were observed to be leached out from the support into

Table 2

Results of homogeneous Heck reactions in NMP and H₂O/NMP (1/2) solvents using organic, inorganic and mixed bases
Reaction conditions: iodobenzene, methyl acrylate, 5 mmol each; Pd(OAc)₂, 0.02 mmol; solvent, 30 ml; temperature, 80°C. In the case of a single base, TEA 5 mmol, Na₂CO₃ 2.5 mmol. In the case of the mixed base, TEA 1 mmol and Na₂CO₃ 2.5 mmol.

Base	Solvent	Time (min)	Conversion (%)	Pd in solvent (ppm)
TEA	NMP	10	32	60
		30	55	60
	NMP/H ₂ O	10	33	2
		30	50	2
Na ₂ CO ₃	NMP	10	0	54
		30	0	48
	NMP/H ₂ O	10	4	16
		30	20	14
TEA + Na ₂ CO ₃	NMP	10	10	66
		30	22	66
	NMP/H ₂ O	10	60	11
		30	80	7

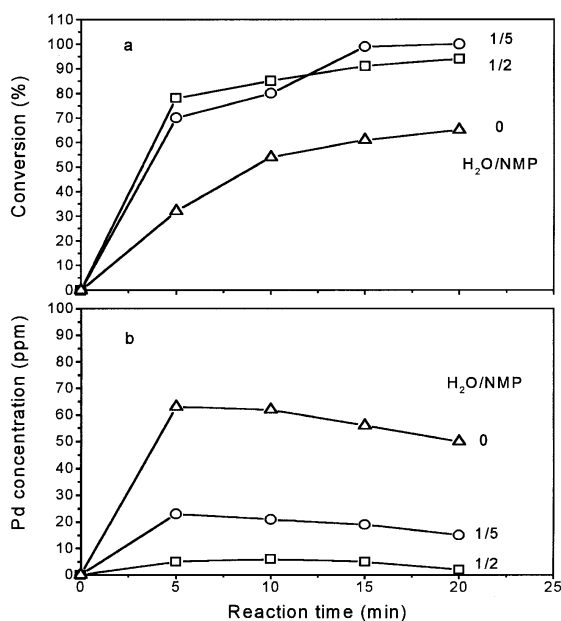


Fig. 4. Influence of water on heterogeneous Heck reaction at 110°C. (a) Conversion determined from the amount of iodobenzene consumed, (b) Pd concentration in the solvent. Reaction conditions: Pd/C 40 mg, iodobenzene and methyl acrylate 5 mmol each, TEA 1 mmol, Na₂CO₃ 2.5 mmol, solvent (NMP and/or H₂O) 30 ml.

the solvent. Fig. 4b gives the change of Pd concentration in the solvent with time. Supported Pd was more significantly dissolved in NMP than in the mixed solvents. For NMP, no colloidal Pd particles were detected by TEM. For the mixed solvent, less Pd leaching was observed at larger water/NMP ratio; however, free Pd particles were present (Fig. 3c, Table 1). In these heterogeneous systems, the reaction should proceed homogeneously with Pd species dissolved in the solvent and so the rate of reaction would be determined by the concentration of these species and their specific activities. As mentioned above, for homogeneous reactions, the activity of Pd species in the mixed solvent is higher than that in pure NMP. This may explain the higher rate of reaction in the water/NMP solvent in spite of the lower concentration of Pd dissolved in the solvent.

The results of Fig. 4 indicate that the present heterogeneous reactions with Pd/C catalyst are

not good for practical application owing to the Pd leaching. In the case of NMP, however, the Pd species dissolved in the solvent can redeposit on the surface of support after the reaction is completed (100% conversion of iodobenzene) as reported elsewhere [7]. In addition, the use of both TEA and Na₂CO₃ is effective in promoting the Pd redeposition as well as the rate of reaction. The supported Pd catalysts were shown to be recyclable without loss of activity. The present results indicate that the addition of water is not useful because it causes the formation of colloidal Pd particles, which are difficult to separate and reuse.

References

- [1] J.P. Genet, M. Savignac, *J. Organomet. Chem.* 576 (1999) 305.
- [2] W.A. Herrmann, V.P.W. Boehm, C.-P. Reisinger, *J. Organomet. Chem.* 576 (1999) 23.
- [3] S. Baese, A. de Meijere, in: F. Diederich, P.J. Stang (Eds.), *Metal-Catalyzed Cross-Coupling Reactions*, Wiley-CVH, Weinheim, 1998, p. 99.
- [4] G.T. Crisp, *Chem. Soc. Rev.* 27 (1998) 427.
- [5] A. de Meijere, F.E. Meyer, *Angew. Chem., Int. Ed. Engl.* 33 (1994) 2379.
- [6] R.F. Heck, in: *Organic Reactions* 27 Wiley, New York, 1982, p. 345.
- [7] F.-Y. Zhao, B.M. Bhanage, M. Shirai, M. Arai, *Eur. J. Chem.*
- [8] F.-Y. Zhao, B.M. Bhanage, M. Shirai, M. Arai, *J. Mol. Catal. A: Chem.* 142 (1999) 383.
- [9] A. Eisenstadt, in: F.E. Herkes (Ed.), *Catalysis of Organic Reactions*, Marcel Dekker, New York, 1998, p. 415.
- [10] L. Djakovitch, K. Koehler, *J. Mol. Catal. A: Chem.* 142 (1999) 275.
- [11] R.K. Ramchandani, B.S. Uphade, M.P. Vinod, R.D. Wakharkar, V.R. Choudhary, A. Sudalai, *Chem. Commun.* (1997) 2071.
- [12] L. Tonks, M.S. Anson, K. Hellegardt, A.R. Mirza, D.F. Thompson, J.M.J. Williams, *Tetrahedron Lett.* 38 (1997) 4319.
- [13] J. Li, A.W.-H. Mau, C.R. Strauss, *Chem. Commun.* 1 (1997) 1275.
- [14] A. Wali, S.M. Pillai, S. Satish, *React. Kinet. Catal. Lett.* 60 (1997) 189.
- [15] J. Kiviaho, T. Hanaoka, Y. Kubotya, Y. Sugi, *J. Mol. Catal. A: Chem.* 101 (1995) 25.
- [16] M. Jikei, Y. Ishida, Y. Seo, M. Kakimoto, Y. Imai, *Macromolecules* 28 (1995) 7924.
- [17] R.L. Augustine, S.T. O'Leary, *J. Mol. Catal. A: Chem.* 95 (1995) 277.
- [18] R.L. Augustine, S.T. O'Leary, *J. Mol. Catal.* 72 (1992) 229.

- [19] B.M. Choudary, M.R. Sarma, *Tetrahedron Lett.* 131 (1990) 1495.
- [20] C.-M. Andersson, A. Hallberg, *J. Org. Chem.* 53 (1988) 235.
- [21] D. Savoia, C. Trombini, A. Umami-Ronchi, G. Verardo, *J. Chem. Soc., Chem. Commun.* (1981) 541.
- [22] S. Klingelhofer, W. Heitz, A. Greiner, S. Oestreich, S. Foester, M. Antonietti, *J. Am. Chem. Soc.* 119 (1997) 10116.
- [23] M.T. Reetz, G. Lohmer, *Chem. Commun.* (1996) 1921.
- [24] M. Beller, H. Fischer, K. Kuehlein, C.-P. Reisinger, W.A. Herrmann, *J. Organomet. Chem.* 520 (1996) 257.
- [25] B.M. Bhanage, M. Shirai, M. Arai, *J. Mol. Catal. A: Chem.* 145 (1999) 69.
- [26] B.M. Bhanage, F.-Y. Zhao, M. Shirai, M. Arai, *Catal. Lett.* 54 (1998) 195.
- [27] B.M. Bhanage, F.-Y. Zhao, M. Shirai, M. Arai, *Tetrahedron Lett.* 39 (1998) 9509.
- [28] J. Kiji, T. Okano, H. Kimura, K. Saiki, *J. Mol. Catal. A: Chem.* 130 (1998) 95.
- [29] M. Beller, J.G.E. Krauter, A. Zapf, *Angew. Chem., Int. Ed. Engl.* 36 (1997) 772.
- [30] J. Kiji, T. Okano, T. Hasegawa, *J. Mol. Catal. A: Chem.* 97 (1995) 73.
- [31] S. Hillers, S. Sartori, O. Reiser, *J. Am. Chem. Soc.* 118 (1998) 2087.
- [32] T. Sugihara, M. Takebayashi, C. Kaneko, *Tetrahedron Lett.* 36 (1995) 5547.
- [33] B.M. Bhanage, Y. Ikushima, M. Shirai, M. Arai, *Tetrahedron Lett.* 40 (1999) 6427.
- [34] N. Shezad, R.S. Oakes, A.A. Clifford, C.M. Rayner, *Tetrahedron Lett.* 40 (1999) 2221.
- [35] S. Cacchi, G. Fabrizi, F. Gasparrini, C. Villani, *Synlett* (1999) 345.
- [36] D.K. Morita, D.R. Pesiri, S.A. David, W.H. Glaze, W. Tumas, *Chem. Commun.* (1998) 1397.
- [37] M.A. Carroll, A.B. Holmes, *Chem. Commun.* (1998) 1395.
- [38] P. Reardon, S. Metts, C. Crittendon, P. Daugherty, E.J. Parsons, *Organometallics* 14 (1995) 3810.
- [39] J.P. Genet, M. Balabane, Y. Legras, *Tetrahedron Lett.* 23 (1982) 331.