4-Methoxypyridine *N*-Oxide: A New Regulator for the Controlled Free Radical Polymerization of Methyl Methacrylate

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Introduction. Anionic polymerization of dienes and vinyl aromatics has been for a long time the only polyaddition reaction endowed with living characteristics.[1] More recently, cationic polymerization of isobutene[2] and vinyl ethers[3] and anionic polymerization of methacrylates[4] has fallen under control, which is also the case nowadays for the free radical polymerization of an increasing number of monomers. Since, in contrast to ionic polymerizations, free radical mechanisms are largely used for the industrial production of a wide range of polymers under not very demanding experimental conditions, a huge research effort is now devoted to screen the most efficient strategies for the free radical polymerization to be rid of transfer and irreversible termination reactions.

The most largely accepted mechanism for the controlled free radical polymerization relies upon a dynamic equilibrium between growing macroradicals (active species) and temporarily terminated macroradicals (dormant species). The accordingly decreased concentration of the propagating species is very beneficial to the first-order propagation step, compared to the second-order termination reactions that are becoming unlikely events. The reversible deactivation of the propagating species by stable counter-radicals, such as TEMPO,[5] has proved highly efficient for the control of the free radical polymerization of a few monomers (styrene, substituted styrene,[6] acrylates,[7] acrylonitrile[8]). *Atom transfer radical polymerization* (ATRP)[9] promoted by transition metal complexes is a variation of the same theme, which extends the control to important additional monomers, such as (meth)acrylates. Nevertheless, contamination of the polymers by the metal may be seen as a serious limitation to the industrial application of ATRP. In an effort to identify new reversible end-capping agents, Colombani[10] has reported that the free radical polymerization of methyl methacrylate and styrene could be controlled by a stable triazolinyl radical. Synthesis of diblock copolymers is claimed although with a broad polydispersity.

In this communication, we would like to report on the capability of a heteroaromatic compound, 4-methoxypyridine *N*-oxide (4-MPNO), to control the free radical polymerization of methyl methacrylate not only in organic solvents but also in at least partly aqueous media.

Experimental Section. Materials. Methyl methacrylate (MMA) from Aldrich was distilled just before use in order to remove the stabilizer. Toluene was also distilled prior to use. Acetonitrile was used as received and water was deionized prior to use. Nitrogen was bubbled through solvents to eliminate molecular oxygen. Cumyl hydroperoxide (CH) was degassed by three freezing−thaw cycles under vacuum. $FeSO_4 \cdot 7H_2O$ and 4-methoxypyridine *N*-oxide (4-MPNO) from Acros were used without any purification. Liquids were transferred under nitrogen by means of syringes or stainless steel capillaries.

Polymerizations. *In Acetonitrile.* $FeSO_4$ (1.67 g, 6 mmol) and 0.77 g of 4-MPNO (6.1 mmol) were added to a 100 mL one-necked round-bottom flask fitted with a three-way stopcock connected to either a nitrogen line or a vacuum pump. Oxygen was removed from the reaction flask by repeated vacuum−nitrogen cycles. Once the flask was filled with nitrogen, acetonitrile was added to the flask. After stirring for 1 h at room temperature, 8 mL of MMA, followed by a degassed solution of 1.1 mL of cumyl hydroperoxide (CH) in 4 mL of acetonitrile, was transferred to the flask. Polymerization was conducted at room temperature under magnetic stirring. Samples were withdrawn all along the polymerization. After evaporation of the residual monomer and solvent, the polymer was dissolved in THF and filtered in order to remove $FeSO_4$ and 4-MPNO. After solvent evaporation and polymer drying under vacuum at 80 °C, the monomer conversion was determined gravimetrically.

Resumption in Toluene. A poly(methyl methacrylate) (PMMA) macroinitiator was prepared as described above. After polymerization for 46 h, solvent and residual monomer were evaporated under vacuum at room temperature. The flask was then filled with nitrogen, and 20 mL of toluene was added. A 1 mL aliquot of this solution was transferred to a 10 mL flask filled with nitrogen, and 3.5 mL of toluene were added. The flask was then placed in an oil bath thermostated at 50 °C. The monomer was added under magnetic stirring, and samples were withdrawn at different reaction times.

In a Water/Acetonitrile Mixture (1/1,v/v). The procedure was exactly the same as that in acetonitrile except that 1.5 molar equiv of 4-MPNO and 1.3 equiv of $FeSO_4 \cdot 7H_2O$ with respect to 1 equiv of CH were used. Water and monomer were first added to the flask, followed by the cumyl hydroperoxide (CH) solution in acetonitrile. Polymerization was conducted at 50 °C.

Characterization. Size exclusion chromatography (SEC) was performed in THF at 40 °C using a Hewlett-Packard 1090 liquid chromatograph equipped with a Hewlett-Packard 1037A refractive index detector. Columns HP PL gel 5μ (10^5 Å, 10^4 Å, 10^3 Å, 100 Å) were calibrated with PMMA standards.

Results and Discussion. The free radical polymerization of MMA has been initiated in acetonitrile at room temperature by the cumyl hydroperoxide/ferrous(II) sulfate redox system. Table 1 shows that the polymerization is slow since only ca. half the initial amount of MMA has been converted after 22 h. When the reaction time is doubled (Table 1, entries 1 and 2), the monomer conversion still increases (from 46 to 73%), whereas M_n decreases (from 9400 down to 7500), which indicates that the polyaddition is not living, as is the

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Table 1. Polymerization of MMA Initiated by Cumyl Hydroperoxide (CH)/Iron(II) Sulfate in Acetonitrile at Room Temperature in the Presence of 4-MPNO or Not[a]

entry	time (h)	4-MPNO/HC	M_n	M_p[b]	M_w/M_n	conversion (%)
1	22	0	9400	16400	1.8	46
2	46	0	7500	14700	1.9	73
3	22	1	4000	5050	1.5	8
4	46	1	7150	14900	1.8	44

[a] Conditions: [MMA] = 2.26 M, [CH] = [4-MPNO] = [$FeSO_4$] = 0.187 M. [b] Molecular weight at the peak bottom.

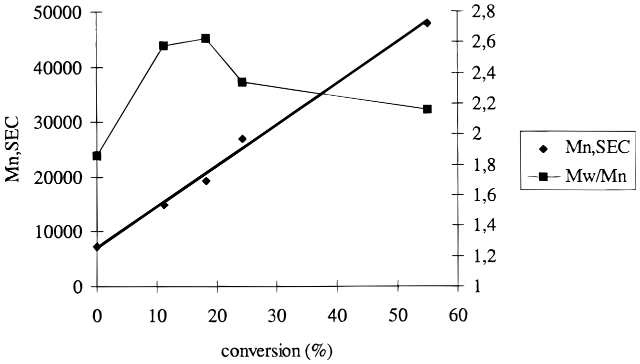


Figure 1. Dependence of M_n and polydispersity on MMA conversion for a resumption experiment in toluene at 50 °C. Conditions: [PMMA] (M_n = 7150, M_w/M_n = 1.8) = 3.3×10^{-3} M, [MMA] = 2.3 M.

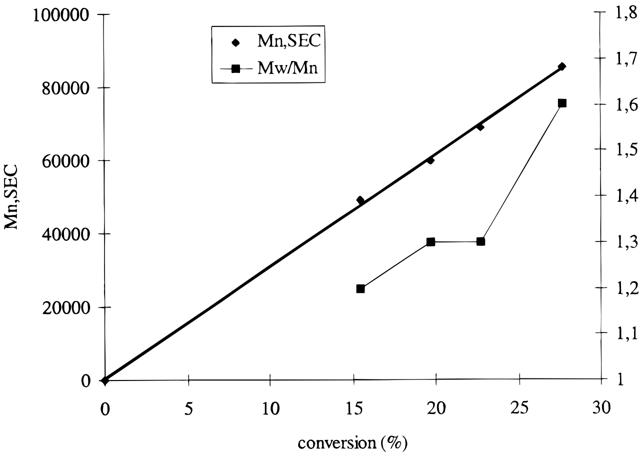
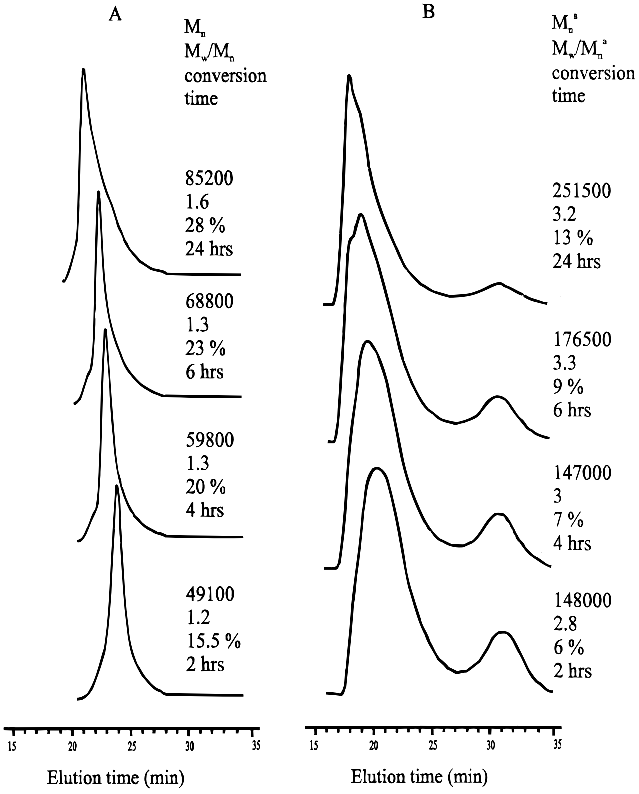


Figure 2. Dependence of M_n and polydispersity upon the MMA conversion in a 1/1 (v/v) water/acetonitrile mixture at 50 °C, in the presence of 4-MPNO [1.5 equiv of 4-MPNO, 1.3 equiv of $FeSO_4$, 1 equiv of CH, 1260 equiv of MMA, H_2O/MMA = 1.25 (v/v)].



* M_n and M_w/M_n of the main peak

Figure 3. SEC chromatograms of PMMA formed in a 1/1 (v/v) water/acetonitrile mixture at 50 °C in the presence (A) and in absence of (B) 4-MPNO [1.5 equiv of 4-MPNO, 1.3 equiv of $FeSO_4$, 1 equiv of CH, 1260 equiv of MMA, H_2O/MMA = 1.25 (v/v)].

case for conventional free radical polymerization. The addition of 4-MPNO in a 1/1 molar ratio with respect to CH changes the polymerization course, since the monomer conversion and somehow the polydispersity are smaller for the same reaction time under the same experimental conditions. More interestingly, M_n significantly increases with monomer conversion (entries 3 and 4, Table 1). These observations indicate that 4-MPNO has a depressive effect on the polymerization rate and that, in parallel, it imparts some control to the reaction.

To know whether this polymerization has living characteristics or not, a monomer-resumption experiment has been carried out at 50 °C in toluene. Indeed, a fresh MMA feed has been added to a previously synthesized PMMA sample, which in the case of living characteristics should be a macroinitiator (M_n = 7150; M_w/M_n = 1.8). This first polymerization step was initiated by the CH/$FeSO_4$ system in acetonitrile in the presence of 4-MPNO (see Experimental Section). A priori, 4-MPNO was used in excess with respect to CH (4-MPNO/CH: 1.5/1 mol/mol) in order to have the best chance of controlling the radical species. Figure 1 shows how $M_{n,SEC}$ of the macroinitiator depends on the conversion of the second MMA feed. The linear dependence observed is evidence that the first PMMA crop consists of chain ends that remain active all along the second polymerization step (constant concentration, suggesting end-capping by labile groups). However, the polydispersity (M_w/M_n) is broad, which cannot be disregarded in drawing final conclusions. Since 4-MPNO is poorly soluble and $FeSO_4$ is completely insoluble in acetonitrile and toluene, the heterogeneity of the reaction medium might be partly responsible for such a broad polydispersity observed. To check this hypothesis and to solubilize these two compounds, water has been added to the polymerization medium.

Methyl methacrylate polymerization has thus been carried out in a 1/1 (v/v) water/acetonitrile mixture at 50 °C, as reported in the Experimental Section. Small droplets of the organic phase are dispersed in the water phase under vigorous stirring, and no precipitation of PMMA is observed during polymerization. Dependence of M_n on the MMA conversion is shown in Figure 2. In the presence of water, this dependence is linear, and the polydispersity remains narrow at least until 25% monomer conversion (M_w/M_n = 1.2−1.3 compared to $M_w/M_n \geq 1.5$ for classical free radical polymerization). At higher monomer conversion, the molecular weight distribution (M_w/M_n) becomes broader, which may indicate

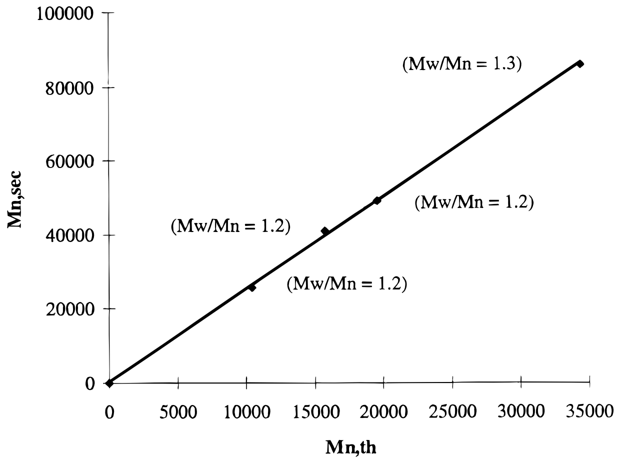


Figure 4. Dependence of the experimental molecular weight ($M_{n,SEC}$) versus the theoretical value ($M_{n,th}$) for selected MMA polymerizations carried out in a 1/1 (v/v) water/acetonitrile mixture at 50 °C in the presence of 4-MPNO [1.5 equiv of 4-MPNO, 1.3 equiv of $FeSO_4$, 1 equiv of CH, H_2O/MMA = 1.25 (v/v)].

the occurrence of termination and/or transfer reactions. The reason for this loss of control is under current investigation. Figure 3 compares the SEC chromatograms for the MMA polymerization conducted in the presence (Figure 3A) and absence (Figure 3B) of 4-MPNO. The very beneficial effect of 4-MPNO is clearly observed. Indeed, in its presence, an otherwise typical bimodal molecular weight distribution becomes basically monomodal and narrow, a very high M_n (even at low conversion) becomes ca. 3 times smaller, and the polymerization stops at higher monomer conversion (30% instead 15% in absence of 4-MPNO).

Additionally, Figure 4 displays the dependence of the experimental M_n ($M_{n,SEC}$) versus the theoretical value $M_{n,th}$ ($M_{n,th} = ([M]_0/[I]_0)M_{w,MMA}\cdot$conversion) when MMA is polymerized in the presence of 4-MPNO in water/acetonitrile mixture (1/1, v/v) at 50 °C, using various $[M]_0/[CH]_0$ molar ratios. A linear plot is observed up to at least 85 000. The slope of the straight line is 2.5, indicating a constant initiator efficiency of 0.4. Furthermore, a relatively narrow polydispersity ($M_w/M_n \approx 1.2$) is observed until at least 40 000.

Conclusions. 4-Methoxypyridine *N*-oxide (4-MPNO) has been shown to promote the controlled free radical polymerization of methyl methacrylate in acetonitrile, thus the formation of PMMA of a predictable high molecular weight and a narrow polydispersity ($M_w/M_n = 1.2-1.3$). This control is reached under mild polymerization conditions including the use of water as cosolvent, which makes the system potentially attractive for industrial applications. It has to be remembered that only PMMA oligomers have been formed by the TEMPO-mediated free radical polymerization, which is known for high control in the case of styrenes and acrylates, although some progress has been recently reported in this field.[11] The limitation of the 4-MPNO-mediated free radical polymerization is the monomer conversion, which does not exceed ca. 30%. The reason for this unexpected observation and the polymerization mechanism are under current investigation. The influence of the main polymerization parameters (nature of solvent and initiator, 4-MPNO and $FeSO_4$ concentrations), controlled polymerization of others monomers and comonomers mixtures, will be the topic of a forthcoming paper.

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