# Hydrodynamic Radii of Polyethylene Glycols in Different Solvents Determined from Viscosity Measurements

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The hydrodynamic radius, $r_h$, of low molar mass polyethylene glycol, $M_{PEG} = (200 \text{ to } 1000)\ \text{g}\cdot\text{mol}^{-1}$, in a homologous series of primary alcohols, acetone, and toluene has been determined from viscosity measurements. The viscosity data have been collected using a fast one-point method as well as a more generally used multipoint method. The results for both approaches are in good agreement. For a given average molar mass of PEG, $r_h$ is the largest in acetone, methanol, and toluene and shows a decrease with the chain length of the alcohol. For the solvents studied, $r_h$ shows an increase with $M_{PEG}$ that can be described adequately by the two-parameter Mark–Houwink equation for $M_{PEG} = (400 \text{ to } 1000)\ \text{g}\cdot\text{mol}^{-1}$. In the range $T = (298.2 \text{ to } 323.2)$ K, the influence of the temperature is not significant.

## Introduction

Polyethylene glycols (PEGs) have a broad range of applications in the pharmaceutical, chemical, cosmetic, and food industries.[1,2] In addition, PEGs are often selected as base case model systems, for example, for studying interaction mechanisms,[3] for characterization of synthetic membranes[4–9] and ion channels.[10] In these studies, the size of the PEG molecules is an important parameter. In solution, the size of PEG molecules is commonly expressed in terms of the hydrodynamic radius ($r_h$), i.e., the radius of the solvated polymer. The hydrodynamic radius can for instance be determined from intrinsic viscosity measurements. Many data can be found for $r_h$ of low molar mass PEG in aqueous solutions,[7,8,11–13] but almost no data are available for low molar mass PEG in the lower alcohols, acetone and toluene.[12] To aid the interpretation of nonaqueous nanofiltration studies, the $r_h$ of PEG [$M_{PEG} = (200 \text{ to } 1000)\ \text{g}\cdot\text{mol}^{-1}$] has been determined in the homologous series of methanol to pentanol, acetone, and toluene. The intrinsic viscosity $[\eta]$ of these PEG solutions has been measured with a fast one-point flow method, and the results have been compared with those of a multipoint method. Using the two-parameter Mark–Houwink relationship,[8] the intrinsic viscosity has been related to the average molar mass of PEG.

## Experimental Section

***Calculations.*** The intrinsic viscosity $[\eta]$, which is a measure for the contribution of a solute to the viscosity of a solution, was determined with a fast one-point method.[4]

$$[\eta] = (2\eta_{sp} - 2 \ln \eta_{rel})^{1/2}/c \qquad (1)$$

where $c$ is the solute concentration; $\eta_{sp}$ is the specific viscosity; and $\eta_{rel}$ is the relative viscosity. The relative viscosity is the ratio of the solution viscosity and the solvent viscosity. It is related to the flow time $t$ of the solution, the flow time $t_0$ of the pure solvent, and the ratio of the density of the solution $\rho$ and the density of the solvent $\rho_0$. The latter ratio is approximated to 1.

$$\eta_{rel} = \frac{\rho}{\rho_0}\frac{t}{t_0}, \quad \eta_{sp} = \eta_{rel} - 1 \qquad (2)$$

The fast one-point method was compared with the more general used multipoint method, in which the intrinsic viscosity $[\eta]$ is obtained from extrapolation of $\eta_{sp}/c$ to zero solute concentration.[14]

$$[\eta] = \lim \xrightarrow[c \to 0]{} \frac{\eta_{sp}}{c} \qquad (3)$$

The hydrodynamic radius $r_h$ was calculated from $[\eta]$ with the Einstein viscosity relation[7,15]

$$r_h = \left(\frac{3[\eta]M_{PEG}}{4\pi 2.5 N_A}\right)^{\frac{1}{3}} \qquad (4)$$

where $M_{PEG}$ is the molar mass of PEG and $N_A$ is the Avogadro constant. The data were fitted to the empirical Mark–Houwink equation by adjusting the polymer, solvent, and temperature specific constants $K$ and $\alpha$[8]

$$[\eta] = KM^{\alpha} \qquad (5)$$

***Materials.*** PEG with an average molar mass of (200, 400, 600, and 1000) g·mol$^{-1}$, methanol (99 %), 1-propanol (99 %), 1-butanol (99 %), 1-pentanol (99 %), and acetone (≥ 99.9 %) were purchased from Sigma-Aldrich, USA. Ethanol (pro analysis) was obtained from Merck, Germany, and toluene (HPLC) was obtained from Biosolve, The Netherlands. All chemicals were used as received.

***Method and Equipment.*** For the one-point method, PEG was dissolved up to a mass fraction of 5 % (accuracy ± 0.001 %). For the multipoint method, the mass fraction was (1 to 5) % for PEG 1000 in pentanol and (2 to 40) % for PEG 200 and 400 in methanol. The flow times (accuracy ± 0.01 s) were measured five times for each sample with a micro-Ubbelohde viscometer from Schott, Germany. The capillaries used were

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**Table 1. Intrinsic Viscosity [$\eta$] of Polyethylene Glycol with $M_{\mathrm{PEG}} = (200, 400, 600, \text{and } 1000)\ \mathrm{g \cdot mol^{-1}}$ Determined with the One-Point Method at $T = (298.2, 303.2, \text{and } 323.2)$ K[a]**

| | $T$/K = 298.2 | | | | $T$/K = 303.2 | | $T$/K = 323.2 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $M_{\mathrm{PEG}}$/g·mol$^{-1}$ | | | | | | | | | |
| solvent | 200 | 400 | 600 | 1000 | 600 | 1000 | 200 | 400 | 600 | 1000 |
| | [$\eta$]/cm$^3$·g$^{-1}$ | | | | | | | | | |
| methanol | 2.42(0.113) | 2.89 | 3.48 | 4.57(0.072) | | 5.12 | 2.16(0.015) | 2.74 | 3.35 | 4.46(0.055) |
| ethanol | 2.02 | 2.58 | 3.09 | 3.91 | 2.91 | | 1.93 | 2.47 | 2.94 | 3.90 |
| 1-propanol | 1.60 | 2.10 | 2.68 | 3.56 | | | 1.73 | 2.29 | 2.69 | 3.83 |
| 1-butanol | 1.43 | 1.90 | 2.32 | 3.13 | | | 1.58 | 1.98 | 2.51 | 3.24 |
| 1-pentanol | 1.02(0.016) | 1.58 | 1.88 | 2.64(0.016) | | 2.91 | 1.22(0.011) | 1.76 | 2.19 | 3.03(0.024) |
| acetone | | | 3.73 | 5.12 | | | | | 3.73 | 4.60 |
| toluene | | | 3.75 | 4.92 | | | | | 3.16 | 4.37 |

[a] The standard deviation of five measurements is given between the brackets.

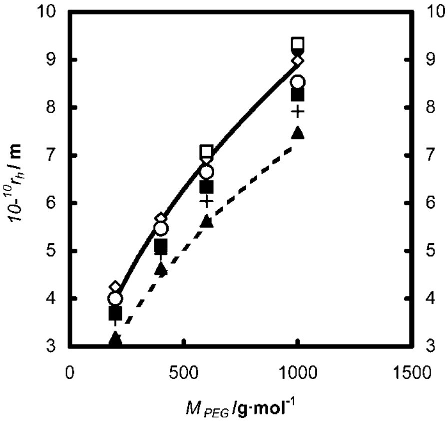

**Figure 1.** Hydrodynamic radius $r_{\mathrm{h}}$ of PEG in ◇, methanol; ○, ethanol; ■, 1-propanol; +, 1-butanol; ▲, 1-pentanol; □, acetone; and ●, toluene at $T$/K = 298.2. The lines represent $r_{\mathrm{h}}$ of PEG in —, methanol; and - - -, 1-pentanol calculated with eq 5. The values of $K$ and α are given in Table 2.

micro-Ubbelohde capillaries nos. 538-10 and 538-20. Measurements were carried out at $T = (298.2, 303.2, \text{and } 323.2)$ K. The temperature was kept constant within ± 0.01 K with a water bath. For the determination of the standard deviation, five samples were prepared and measured. The standard deviation reflects the uncertainty in concentration $c$, temperature $T$, and measured flow times $t_0$ and $t$.

## Results and Discussion

The values of [$\eta$] determined with the one-point method are given in Table 1, and the corresponding $r_{\mathrm{h}}$ is presented in Figures 1 and 2. Because PEG has a molecular weight distribution, [$\eta$] measured and $r_{\mathrm{h}}$ calculated are average values. For a given $M_{\mathrm{PEG}}$, $r_{\mathrm{h}}$ is the largest in acetone, methanol, and toluene and shows a decrease with the chain length of the alcohol. The variation of $r_{\mathrm{h}}$ is in accordance with the polarity of the solvents, which is the highest for acetone, methanol, and toluene and decreases with the chain length of the alcohols. For more polar solvents, $r_{\mathrm{h}}$ of the polar PEG is expected to be larger. For all the solvents measured, $r_{\mathrm{h}}$ increases with $M_{\mathrm{PEG}}$ as the chain length of the PEG molecule increases. In the range $T = (298.2 \text{ to } 323.2)$ K, the influence of temperature is not significant. The $r_{\mathrm{h}}$ values of PEG 200, 400, and 1000 in methanol and pentanol determined with the multipoint method are given in Table 2. Extrapolation was done using a linear relation. The results for the multipoint method are within the confidence interval of 99 % of the one-point method (Table 3). It can be concluded that the results of both methods are in agreement.

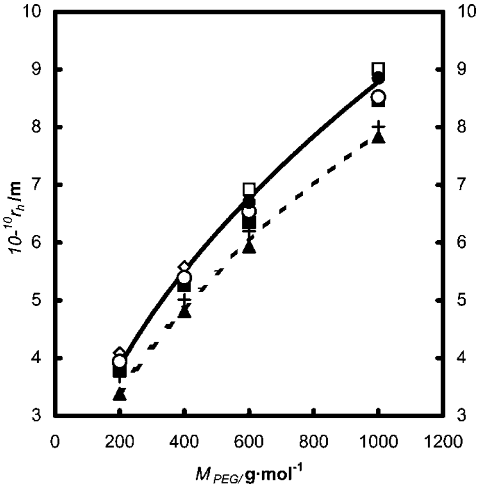

**Figure 2.** Hydrodynamic radius $r_{\mathrm{h}}$ of PEG in ◇, methanol; ○, ethanol; ■, 1-propanol; +, 1-butanol; ▲, 1-pentanol; □, acetone; and ●, toluene at $T$/K = 323.2. The lines represent $r_{\mathrm{h}}$ of PEG in —, methanol; and ---, 1-pentanol calculated with eq 5. The values of $K$ and α are given in Table 2.

**Table 2. Hydrodynamic Radius $r_{\mathrm{h}}$ of Polyethylene Glycol with $M_{\mathrm{PEG}} = (200, 400, \text{and } 1000)\ \mathrm{g \cdot mol^{-1}}$ in Methanol and Pentanol Determined with (a) the One-Point Method and (b) the Multipoint Method at $T = (298.2, 303.2, \text{and } 323.2)$ K**

| | $M_{\mathrm{PEG}}$/g·mol$^{-1}$ | | | |
|---|---|---|---|---|
| | 200 | 400 | 1000 | 1000 |
| solvent | $T$/K = 323.2 | $T$/K = 298.2 | $T$/K = 298.2 | $T$/K = 303.2 |
| | $10^{-10} r_{\mathrm{h}}$/m | | | |
| methanol | 4.10$^{a}$, 4.07$^{b}$ | 5.68$^{a}$, 5.44$^{b}$ | | 9.33$^{a}$, 9.16$^{b}$ |
| 1-pentanol | | | 7.47$^{a}$, 7.47$^{b}$ | |

The [$\eta$] for PEG 1000 in toluene given in Table 1 at $T$/K = 298.2 is approximately 2.5 times larger as compared to the value at $T$/K = 308.2 reported by Thomas;[12] the corresponding $r_{\mathrm{h}}$ is about 30 % larger. Thomas[12] does not provide sufficient experimental details to identify the origin of this difference. Possibly, the difference is due to the different nature of the PEG samples (supplier, molecular weight distribution, etc.). Similar differences have been observed for the $r_{\mathrm{h}}$ of PEG in aqueous solutions, as can be seen in Table 4.

The applicability of the Mark–Houwink relationship implies a linear relation between ln [$\eta$] and ln $M_{\mathrm{PEG}}$. In Figure 3, this linear relation is observed for PEGs with an average molar mass of 400 and higher. The corresponding values of $K$ and α are presented in Table 5. For PEG 200, significant deviations from the linear relation are observed. These deviations can be due to an asymmetric molar mass distribution typical for low molar mass oligomers (a PEG oligomer with a molar mass of 200 consists of only four monomers) or to the linear shape of the molecule. Linear polymers such as PEG have flexible chains

**Table 3. Confidence Interval of 99 % of the Hydrodynamic Radius $r_h$ of Polyethylene Glycol with $M_{\mathrm{PEG}}$ = (200 and 1000) g·mol$^{-1}$ in Methanol and 1-Pentanol Determined with the One-Point Method at $T$ = (298.2 and 323.2) K**[a]

| | $M_{\mathrm{PEG}}$/g·mol$^{-1}$ | | | |
|---|---|---|---|---|
| | 200 | 200 | 1000 | 1000 |
| solvent | $T$/K = 298.2 | $T$/K = 323.2 | $T$/K = 298.2 | $T$/K = 323.2 |
| | Confidence Interval of 99 % of $10^{-10}r_h$/m | | | |
| methanol | 4.12 to 4.38 | 4.01 to 4.17 | 8.88 to 9.08 | 8.84 to 8.98 |
| 1-pentanol | 3.15 to 3.22 | 3.36 to 3.45 | 7.43 to 7.53 | 7.77 to 7.89 |

[a] Confidence interval of 99 % = average of five measurements $\pm \sigma/\sqrt{n}\cdot 2.776$ , where $\sigma$ is the standard deviation and $n$ is the number of measurements.

**Table 4. Hydrodynamic Radius $r_h$ Found in the Literature of Polyethylene Glycol with $M_{\mathrm{PEG}}$ = (200 to 1000) g·mol$^{-1}$ Solved in Water at Room Temperature**[6,8,11,13] **and $T$/K = 308.2**[12a]

| | $M_{\mathrm{PEG}}$/g·mol$^{-1}$ | | | |
|---|---|---|---|---|
| | 200 | 400 | 600 | 1000 |
| | $10^{-10}r_h$/m | | | |
| Causserand[6] | 5.2 | 7.6 | 9.5 | 12.6 |
| Riedl[8] | 4.5 | 5.7 | 7.5 | 9.7 |
| Fee[11] | 3.70 | 5.45 | 6.83 | 9.09 |
| Thomas[12] | | 4.73 | | 7.79 |
| Tam[13] | 3.4 | 4.9 | 6.1 | 8.0 |

[a] Causserand[6] used a constant of 1 instead of 2.5 in (4).

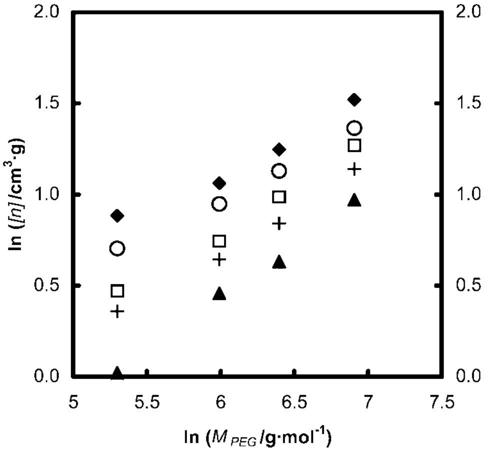

**Figure 3.** Intrinsic viscosity as ln [$\eta$] of PEG in ◆, methanol; ○, ethanol; □, 1-propanol; +, 1-butanol; and ▲, 1-pentanol at $T$/K = 298.2 (results at $T$/K = 323.2 show the same trend, so they are not shown here).

**Table 5. Mark–Houwink Parameters $K$ and $\alpha$ Determined for $M_{\mathrm{PEG}}$ = (400 to 1000) g·mol$^{-1}$ in Different Alcohols at $T$ = (298.2 and 323.2) K**

| | $T$/K = 298.2 | | $T$/K = 323.2 | |
|---|---|---|---|---|
| solvent | $K$ | $\alpha$ | $K$ | $\alpha$ |
| methanol | 0.14 | 0.50 | 0.11 | 0.53 |
| ethanol | 0.17 | 0.45 | 0.12 | 0.50 |
| 1-propanol | 0.07 | 0.58 | 0.07 | 0.57 |
| 1-butanol | 0.07 | 0.55 | 0.08 | 0.54 |
| 1-pentanol | 0.05 | 0.56 | 0.06 | 0.57 |

and approximate a globular shape in solution. Oligomers with only four units are relatively inflexible and deviate from this globular shape. Sadron and Rempp[8] also observed upward deviations from the Mark–Houwink relation for low molar mass oligomers and proposed a modified equation. Use of this modified equation did not result in a better fit of the experimental data. From the Mark–Houwink relation, $r_h$ has been calculated with the fitted parameters $K$ and $\alpha$ (Table 5). The results are plotted as lines in Figures 1 and 2, for methanol and 1-pentanol. Although the Mark–Houwink relation is only applicable for PEG with an average molar mass of 400 and higher, the derived value for $r_h$ of PEG 200 differs only slightly from the experimental data.

## Conclusions

The one-point flow method can be applied to determine the intrinsic viscosity of low molar mass PEG in primary alcohols, acetone, and toluene. From the viscosity data the hydrodynamic radius, $r_h$ of PEG can be determined. For a given average $M_{\mathrm{PEG}}$, $r_h$ is the largest in acetone, methanol, and toluene and shows a decrease with the chain length of the alcohol. The hydrodynamic radius shows an increase with $M_{\mathrm{PEG}}$ that can be described adequately by the Mark–Houwink relationship for $M_{\mathrm{PEG}}$ = (400 to 1000) g·mol$^{-1}$. In the range $T$ = (298.2 to 323.2) K, the influence of the temperature is not significant.

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