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Molecular weight distribution characterization of hydrophobe-modified hydroxyethyl cellulose by size-exclusion chromatography

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ABSTRACT

Size-exclusion chromatography (SEC) of hydrophobe-modified hydroxyethyl cellulose (HmHEC) is challenging because polymer chains are not isolated in solution due to association of hydrophobic groups and hydrophobic interaction with column packing materials. An approach to neutralize these hydrophobic interactions was developed by adding β-cyclodextrin (β-CD) to the aqueous eluent. SEC mass recovery, especially for the higher molecular weight chains, increased with increasing concentration of β-CD in the eluent. A β-CD concentration of 0.75 wt% in the eluent was determined to be optimal for the HmHEC polymers studied. These conditions enabled precise determinations of apparent molecular weight distributions exhibiting less than 2% relative standard deviation in the measured weight-average molecular weight (M_W) for five injections on three studied samples and showed no significant differences in M_W determined on two different days. The developed technology was shown to be very robust for characterizing HmHEC having M_W from 500 kg/mol to 2000 kg/mol, and it can be potentially applied to other hydrophobe-modified polymers.

1. Introduction

Cellulose ethers that are lightly functionalized with long chain alkyl groups have unique solution rheology properties [1–3] that make them useful as thickeners in many applications and products such as household cleaning [4], personal care [5,6], latex paint formulations [7], and construction products [8,9]. Hydrophobe-modified hydroxyethyl cellulose (HmHEC) is one example, which is synthesized by adding hydrophobic groups (i.e., $C_{16}H_{33}$) to the starting material hydroxyethyl cellulose (HEC) having an ethylene oxide molar substitution (EO MS) of about 2. The general chemical structures of HEC and HmHEC are depicted in Fig. 1. The hydrophobe degree of substitution (hydrophobe DS) is defined as the molar ratio of hydrophobic groups to anhydroglucose repeat units. The typical hydrophobe DS in HmHEC is usually quite low (typically between 0.004 and 0.010), and low levels of hydrophobe substitution can have profound effects on the solution rheology of HmHEC. Association of the hydrophobes (hydrophobic aggregation) provides pseudo cross-linking sites, preventing the polymer chains from contracting with increasing temperature. This structural modification enables the unique elevated temperature viscosity retention that is crucial for elevated temperature application of certain HmHEC polymers above 100 °C. This elevated temperature viscosity retention is highly dependent on the molecular weight of HmHEC [10]. However, the hydrophobic modification of cellulose ether derivatives presents problems for size-exclusion chromatography (SEC) analysis. Accurate molecular weight distribution (MWD) analysis by SEC requires isolated chains in solution, and this is not possible in pure water because of the hydrophobic association between HmHEC polymer chains. Additionally, the hydrophobes may interact with SEC column packing materials so that HmHEC adsorbs to the column and will not elute. For this reason, the SEC recovery for HmHEC was less than 20% when a typical aqueous SEC mobile phase for HEC, water with a trace of NaN_3, was used. A literature search revealed a published abstract on the molecular weight distribution characterization of hydrophobe-modified hydroxyethyl cellulose ethers by SEC, but it did not provide details of the experimental conditions [11].

Neutralizing hydrophobic interaction is a critical requirement for a successful SEC condition for characterizing the MWD of HmHEC. Several approaches for sequestering hydrophobes on HmHEC have been reported in the literature. These include adding various surfactants to the aqueous HmHEC solution to disrupt the hydrophobe aggregates and decrease the solution viscosity

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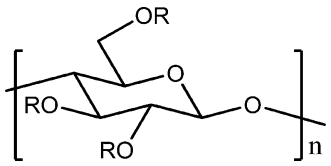

Fig. 1. General chemical structure of anhydroglucose repeat unit of HEC and HmHEC. HEC: R = $(CH_2CH_2O)_nH$, or H, and EO MS = 2; HmHEC: R = $(CH_2CH_2O)_nR'$, H, or $C_{16}H_{33}$, and R′ = H or $C_{16}H_{33}$, EO MS = 2 and hydrophobe DS ($C_{16}H_{33}$) = 0.004 to 0.010.

[12–14]; dissolving HmHEC in mixed solvents [15]; and adding cyclodextrin as a co-solute with HmHEC in aqueous solution to form inclusion complexes [16–18].

Cyclodextrins belong to a family of cyclic oligosaccharides, and α, β, γ are three well-known cyclodextrins that comprise six to eight α (1→4) linked glucopyranose units, respectively [19–21]. The outside of the molecular cavity is hydrophilic and consists of the primary alcohol units on the glucose rings, whereas the inner surface of the cavity is slightly less hydrophilic than the exterior and consists of the ether-like anomeric oxygen atoms and the secondary alcohols on the glucose ring. In an aqueous solution, the slightly apolar cyclodextrin cavity is occupied by water molecules which are energetically unfavored (polar–apolar interaction), and therefore can be readily substituted by less polar molecules. Thus, the cyclodextrin molecules may bind non-polar, suitably-sized aliphatic and aromatic compounds such as aroma compounds and lipophilic drugs. They may bind in 1:1, 2:1 and 1:2 ratios depending on the molecules involved. The binding is driven by the enthalpic and entropic gain from reduction of the hydrophobe-aqueous surface and the release of water molecules from the cavity to the bulk phase.

Because cyclodextrin is known to form inclusion complexes with hydrophobes in HmHEC and has similar chemical structure as HmHEC (similar anhydroglucose repeat unit), the authors believed that use of cyclodextrin as a modifier would neutralize hydrophobic interactions to provide ideal SEC separation conditions.

In this paper, the use of β-cyclodextrin (β-CD) for development of ideal SEC conditions for characterization of HmHEC MWD is discussed. HmHEC and its precursor HEC were analyzed by the developed SEC conditions and MWD plots were compared to evaluate the approach. The developed conditions were applied to the characterization of HmHEC with PEO apparent M_W from 500 to 2000 kg/mol and can potentially be applied for other hydrophobe-modified cellulose ether materials. Additionally, SEC-multi-angle laser light scattering (SEC-MALLS) results for absolute MWD of HEC are also reported and compared to those obtained by PEO calibration, as well as, HEC broad standard calibration.

2. Experimental

2.1. Chemicals

All chemicals and molecular weight standards were purchased from vendors and were used as received. Deionized water (DI Water) was filtered through a 0.2-μm nylon cartridge prior to use. Sodium azide, 99.99+%, β-cyclodextrin (β-CD), >98%, and bovine serum albumin (BSA) monomer, ~98%, were purchased from Sigma–Aldrich. Polyethylene oxide (PEO) narrow molecular weight standards were purchased from TOSOH (Montgomeryville, PA). Toluene, HPLC grade, was purchased from Fisher Scientific. HEC and HmHEC materials were obtained from The Dow Chemical Company. The EO MS in HEC and HmHEC is about 2, and the hydrophobe DS is given in Table 1. The EO MS and hydrophobe DS values were determined using the Zeisel method and gas chromatography [22].

Table 1
Sample information.

Sample name	Hydrophobe DS
HEC 600	0
HEC 700	0
HEC 1400	0
HEC 1500	0
HEC 2000	0
HmHEC 700	0.0071
HmHEC 1000	0.0090
HmHEC 1300	0.0082
HmHEC 1500A	0.0044
HmHEC 1500B	0.0053
HmHEC 1500C	0.0062

2.2. SEC-MALLS absolute MWD characterization of HEC

2.2.1. SEC eluent

The eluent consisting of 0.05 wt% NaN_3 was prepared by dissolving NaN_3 in DI water, and was re-circulated through a 0.04-μm nylon cartridge for 4–5 h to remove particulate impurities prior to use.

2.2.2. Sample preparation

Sample solutions were prepared in the SEC eluent to minimize interference from any solvent mis-matched peak in differential refractive index detector (DRI) chromatogram. To ensure that polymer chain overlaps were minimized, the desired sample concentration was set at about 0.3 mg/mL. Polymer concentrations were corrected for ash and volatiles, and the ash and volatiles were measured as described in ASTM method of D-2364-01. Solutions were slowly shaken on a flat-bed shaker for 2–3 h at ambient temperature to dissolve the samples, and then were stored overnight in a refrigerator set at 4 °C for complete hydration and dissolution. On the second day, solutions were shaken again for 1–2 h at ambient temperature. All solutions were filtered through a 0.45-μm nylon syringe filter prior to injection.

2.2.3. SEC system

SEC Pump was Waters Alliance 2690 set at a flow rate of 0.5 mL/min with continuous vacuum degassing. A filter that consisted of two layers of 0.2-μm nylon membrane was installed between the pump outlet and the injection valve. Injection was performed by Waters Alliance 2690 programmed to inject 100 μl of solution. Separation was carried out by two TSK GEL GMPW columns (7.5 mm ID × 30 cm, 17-μm particles, 100–1000 Å pores nominal) held at 28 °C. Detectors were Wyatt DAWN DSP MALLS detector connected with a Wyatt Optilab rEX DRI detector. The Wyatt DAWN DSP was equipped with a red laser operating at a wavelength of 632.8 nm and operated at room temperature. The Wyatt Optilab rEX DRI detector was operated at 28 °C.

2.2.4. Calibration and data process

The Wyatt DAWN DSP was calibrated with HPLC grade toluene filtered through a 0.05-μm syringe filter. The individual light scattering detectors were normalized to the 90° light scattering detector using mono-dispersed bovine serum albumin (BSA) monomer as the isotropic scatter. The inter-detector delay volume was determined by aligning the 90° light scattering peak with DRI peak of BSA.

The signals from the MALLS and DRI detectors were analyzed using ASTRA V software, version 5.3.2. M_W and radius of gyration R_g were determined at each SEC elution volume increment. To obtain these metrics, light scattering signals covering the angular range from 25.8° to 132.2° were least squares fit to a first order polynomial according to the Zimm formalism. A dn/dc (the specific refractive index increments) of 0.140 mL/g for all studied HEC