Multidetector thermal field-flow fractionation as a unique tool for the tacticity-based separation of poly(methyl methacrylate)-polystyrene block copolymer micelles

Guilaume Greyling, Harald Pasch*

Department of Chemistry and Polymer Science, University of Stellenbosch, Private Bag X1, 7602 Stellenbosch, South Africa

ABSTRACT

Poly(methyl methacrylate)-polystyrene (PMMA-PS) micelles with isotactic and syndiotactic coronas are prepared in acetonitrile and subjected to thermal field-flow fractionation (ThFFF) analysis at various conditions of increasing temperature gradients. It is shown for the first time that multidetector ThFFF provides comprehensive information on important micelle characteristics such as size (D_h), shape (R_g/R_h), aggregation number (Z), thermal diffusion (D_T) and Soret coefficients (S_T) as a function of temperature from a single injection. Moreover, it is found that micelles exhibit a unique decreasing trend in D_T as a function of temperature which is independent of the tacticity of the corona and the micelle preparation method used. It is also demonstrated that ThFFF can monitor micelle to vesicle transitions as a function of temperature. In addition to ThFFF, it is found from DLS analysis that the tacticity of the corona influences the critical micelle concentration and the magnitude to which micelles expand/contract with temperature. The tacticity does not, however, influence the critical micelle temperature. Furthermore, the separation of micelles based on the tacticity of the corona highlight the unique capabilities of ThFFF.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Thermal field-flow fractionation (ThFFF) is a subtechnique of field-flow fractionation that employs a temperature gradient across an open, ribbon-like channel to fractionate analyte molecules according to size or chemical composition [1,2]. Analytes subjected to a temperature gradient migrate from the hot to the cold wall (accumulation wall) of the channel. Such a lateral migration of analytes due to a temperature gradient is characterised by the thermal diffusion coefficient, D_T. Thermal diffusion is counteracted by normal diffusion which is the migration of analyte molecules away from the accumulation wall towards the center of the channel due to increasing analyte concentration. Normal diffusion is characterised by the normal diffusion coefficient, D [3]. Furthermore, diffusion is dependent on the size of the analyte molecules in solution, whereas thermal diffusion is independent of size and dependent on, among other factors, the chemical nature of the analyte molecules and the solvent [1,4].

Within the channel with the flowing carrier, a parabolic flow velocity profile forms which results in faster flow streams towards the center of the channel and slower streams towards the accumulation wall [1]. Retention is determined by the average position of the analyte molecules in the flow velocity profile and therefore by their mean distance from the accumulation wall [4]. Thus, the further the analyte molecules are from the accumulation wall (faster flow streams), the shorter the retention time. The average distance from the accumulation wall is determined by the interplay between D_T and D. This interplay is described by the Soret coefficient, S_T, where $S_T = D_T/D$ [1,5]. Therefore, analyte molecules with similar S_T values will reside in similar flow streams and co-elute. Furthermore, D_T appears to be dominated by the monomers preferentially located in the outer region of solvated polymer molecules [6]. As with all FFF techniques (operating in normal mode), ThFFF elution order is from small to large size analytes [1,4].

ThFFF is predominantly used in the characterization of analytes in organic solvents and it has been demonstrated that ThFFF can be used for the characterization of a variety of analytes such as homopolymers, polymer blends, copolymers, microgel samples, particles, colloids and aggregates [1,2,7–11]. It has also been demonstrated that the fractionation capabilities of ThFFF are not limited to size and chemical composition but extend to polymer microstructure [12,13]. ThFFF is a powerful alternative to commonly used column-based techniques, such as size exclusion chromatography (SEC), as the relatively gentle fractionation conditions

and the absence of a stationary phase enable ThFFF to readily fractionate a variety of high molecular weight and fragile compounds without degradation taking place [4]. Moreover, sample preparation steps such as filtering, which could affect sample composition, are not often required prior to ThFFF analysis.

The unique features of ThFFF make it a suitable technique for the characterization of high molecular weight self-assemblies such as micelles. Micelles are formed by the self-assembly of e.g. block copolymers that are dissolved in a selective solvent. A selective solvent is a thermodynamically good solvent for one of the blocks but a poor solvent/precipitant for the other [6,14–16]. Block copolymer micelles consist of a core formed by the insoluble block and a corona formed by the soluble block. The critical concentration at which the block copolymers start to self-assemble into micelles is called the critical micelle concentration, CMC. Below the CMC only molecularly dissolved copolymer chains, or unimers, are found whereas above the CMC, micelles are in equilibrium with unimers [15,17]. Closely related to the CMC is the critical micelle temperature, CMT. The CMT is the temperature above which micelles disassemble into unimers due to decreasing solvent selectivity with increasing temperature [15,18]. Other important micelle characteristics include Z (aggregation number), R_g (radius of gyration), R_h (hydrodynamic radius) (or hydrodynamic diameter, D_h) and R_g/R_h (shape factor).[17]

Micelles are appealing for applications in fields such as colloid stabilization, drug delivery, coating and microreactor applications due to their stability and versatility and are characterised by various techniques [19–21]. These include techniques such as electron microscopy (SEM and TEM), atomic force microscopy (AFM), NMR, fluorescence spectroscopy, dynamic light scattering (DLS), static light scattering (SLS) and SEC [15,22,23]. For electron microscopy the sample is dried and only observed over a narrow scale range. Furthermore, although information regarding size and size distributions can be obtained, information regarding corona chemical composition cannot. AFM suffers from the shape and size of the micelles being affected by tip-convolution effects, specific interactions between the substrate the block copolymer or by the flattening of the micelles on the substrate while fluorescence spectroscopy is not suitable for routine use and care must be taken to avoid aggregation between the probe and unimers below the CMC [15,24].

DLS and SLS enables the analysis of analytes in solution but only information regarding size and size distributions can be obtained whereas NMR yields information regarding the average corona chemical composition but it cannot reveal any information regarding size and size distributions present in the sample. Lastly, SEC has been employed to characterize the unimer-micelle equilibrium and also to determine molecular weights of micelles [14,15]. However, several studies have shown that strong perturbation in the unimer-micelle equilibrium, disassembly of micelles, analyte trapping in the column and adsorption on the column packing occur during analysis [14,15].

Recently, flow field-flow fractionation (FlFFF) and asymmetric flow field-flow fractionation (AF4) have been used to characterize micelles and other self-assemblies, such as polymersomes, according to size, shape and molecular weight [22,23,25,26]. Moreover, it was demonstrated that in some instances only AF4 could reveal the presence of size distributions that were not observed by traditional techniques such as DLS [23,25]. In addition to AF4, ThFFF has also been shown to be a suitable technique for the analysis of micelles with different core compositions [27].

To date, the question whether it is possible to fractionate micelles based solely on differences in the tacticity of the corona has yet to be investigated. This is a pertinent question as anisotropic micelles with mixed corona compositions, such as patchy, multicompartment and Janus micelles, have attracted

significant attention in recent years due to their unique morphologies and potential applications [28]. Moreover, these self-assemblies lack suitable analytical techniques to provide comprehensive information on both corona composition as well as on size and shape distributions [28].

In the present study, for the first time it is demonstrated that, in addition to determining important micelle characteristics such as size, shape and aggregation number as a function of temperature, ThFFF is capable of fractionating micelles based on differences in the tacticity of the corona. This study describes the application of ThFFF coupled online to ultraviolet (UV), multiangle laser light scattering (MALLS), differential refractive index (dRI) and dynamic light scattering (DLS) detectors to simultaneously determine changes in micelle characteristics such as R_g/R_h, D_h, R_g, Z, D_T and S_T as a function of temperature for PMMA-PS micelles with different corona tacticities.

2. Materials and methods

2.1. Materials

PMMA-PS block copolymers with different PMMA tacticities were purchased from Polymer Source Inc. (Montreal, Canada). HPLC grade acetonitrile (ACN) was purchased from Sigma–Aldrich (South Africa).

2.2. Micelle preparation

PMMA-PS block copolymers with high isotactic (iPMMA-PS) and high syndiotactic (sPMMA-PS) PMMA content were used to prepare micelles in ACN by both the co-solvent and nanoprecipitation methods reported in the Supplementary material [25,29]. ACN is a theta solvent for PMMA and a non-solvent for PS. Samples prepared by the nanoprecipitation method are indicated hereafter by the notation (N). Furthermore, micelle formation was confirmed by ^1H NMR as described in the literature [15,29].

2.3. Thermal field flow fractionation

The thermal FFF system TF2000 (Postnova Analytics, Landsberg, Germany) was coupled online to an UV (PN 3212 at 254 nm, Postnova Analytics), MALLS (PN 3070, Postnova Analytics), dRI (PN 3150, Postnova Analytics) and DLS detectors (Zen 1600, Malvern Instruments, Worcestershire, UK). The TF2000 channel had a tip-to-tip length of 45.6 cm, breadth of 2 cm, thickness of 127 μm and void volume of 1.14 mL. Carrier flow is generated by a isocratic pump (PN 1130, Postnova Analytics) and the samples are introduced into the channel via a Rheodyne manual injection valve. Values for S_T were calculated as shown in the introduction while values for D_T were calculated according to [1]:

$$D_T = \frac{6Dt_r}{\Delta T t^\circ}$$

Where t^o is the void time, t_r is the retention time of the sample and ΔT is the temperature difference between the hot and cold wall. D_h and D values were determined by DLS analysis. ACN was used as carrier liquid with a flow rate of 0.3 mL min^{-1} and a dn/dc value of 0.136 mL g^{-1} for PMMA in ACN was used for the micelles [10]. Samples were injected through a 100 μL capillary sample loop and triplicate analysis of each sample was performed under non-overloading sample concentrations.

2.4. ^1H NMR

The NMR experiments were conducted on a 400 MHz Varian Unity Inova spectrometer (Agilent/Varian, Palo Alto, California,