A new and facile method for measurement of apparent density of monodisperse polymer beads

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ABSTRACT

The apparent density, an intrinsic physical property of polymer beads, plays an important role in the application of beads in micro-total analysis systems and separation. Here we have developed a new, facile and milligram-scale method to describe the motion of beads in aqueous solution and further detect the apparent density of beads. The motion of beads in solutions is determined by the viscosity of solutions and the density difference between beads and solutions. In this study, using various glycerol aqueous solutions with certain viscosities and densities, the motion time (i.e. floating or sedimentation time) of hybrid polymer beads was experimentally measured and theoretically deduced, and consequently, the apparent density of monodisperse beads can be quickly and easily calculated. The results indicated that the present method provided a more precise way to predict the movement of hybrid beads in aqueous solution compared with the approach for commercial use. This new method can be potentially employed in flow cytometry, suspension stability, and particle analysis systems.

1. Introduction

In micro-total analysis systems (µTAS), monodisperse hybrid polymer beads have been widely used in many fields of biological analysis, high-throughput screening, and immunoassay and among others [1–3]. However, due to the unmatched densities of hybrid polymer beads and aqueous solutions [4], a well suspension of polymer beads in aqueous solutions cannot be achieved, resulting in a higher measurement error and lower signal-to-noise ratio [5]. Obviously, a feasible solution is adjusting either the densities of polymer beads [4] or those of aqueous solutions (e.g. an addition of glycerol or sucrose [6]). Although, the densities of polymer beads can be measured by a density meter (ASTM D4052) [7], the measurement of apparent densities of hybrid beads is still a grand challenge due to hybridization of nanoparticles, surface hydrophilic liquid layer [8] and inner nano-scale pores [9]. Here a simple and robust method that can precisely describe the movement of hybrid polymer beads in glycerol aqueous solution, was demonstrated, and further applied to the measurement of apparent density. And it also has potential use in flow cytome-

try, microfluidics chips, bead suspensions, and particle analysis systems.

2. Materials and methods

2.1. Materials

Monodisperse polymer beads (PC06N/6182, with carboxyl group, size 9.77 µm) were purchased from Bangs Laboratories, Inc. Uniform magnetic beads were obtained from Micromod (micromod Partikeltechnologie GmbH, Micromer®-M, Prod.-No. 08-01-104, with amine group, size 10 µm). The densities of polymer beads and magnetic beads provided by vendor are 1.062 and 1.1 g/cm³, respectively. Sodium dodecyl sulfate (SDS) and glycerol (≥99% (GC)) was procured from Sigma. The water used in all experiments was de-ionized water.

2.2. Motion of beads in glycerol–water mixtures

0.5 mg of polymer beads or commercial magnetic beads was dried under air at room temperature and re-dispersed in a 1.5 mL vial containing 0.5 mL of glycerol–water mixtures. Owing to the lower or higher densities of beads compared with those of glycerol solutions, the beads were buoyed up or sunk down in the
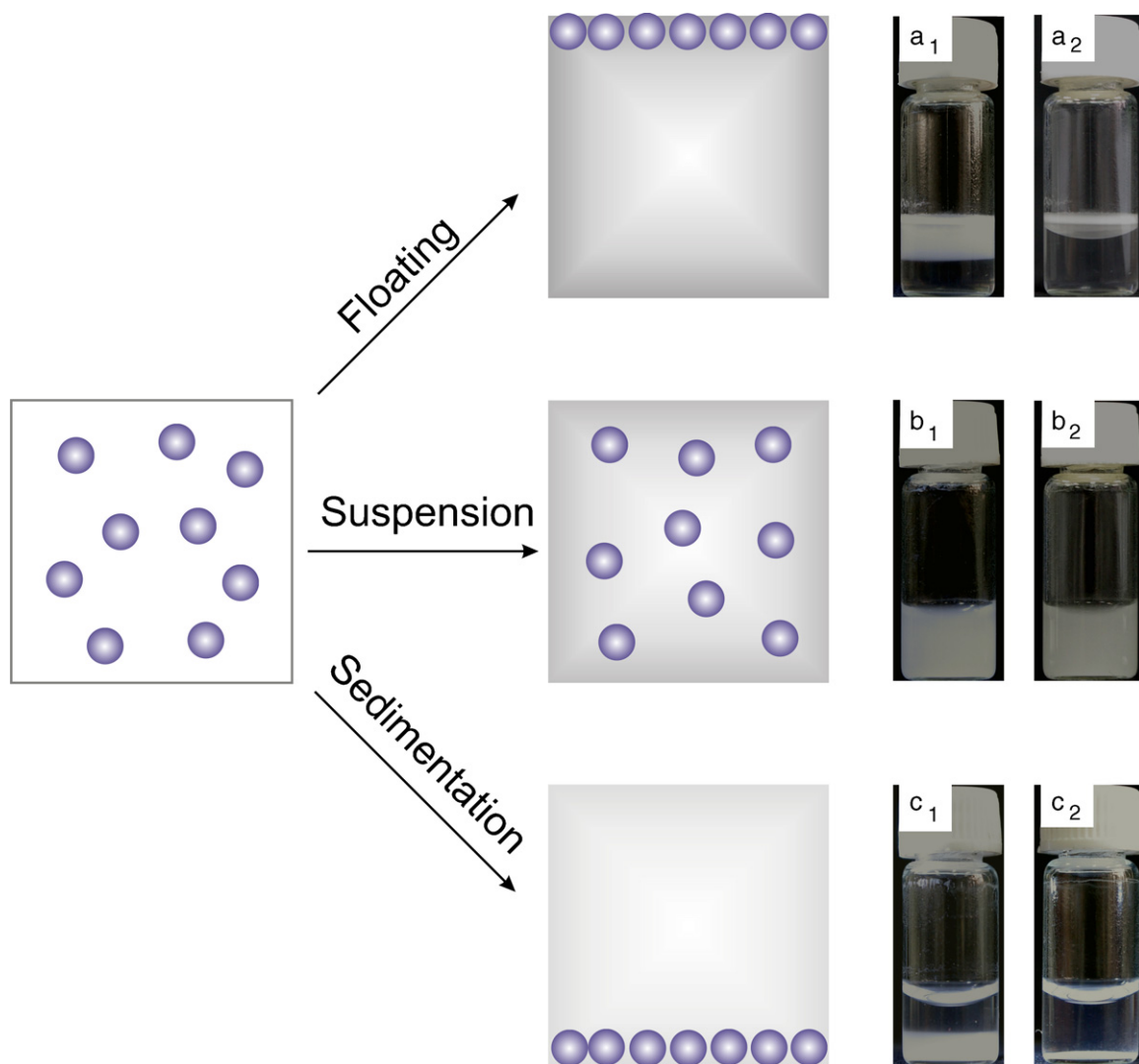
Fig. 1. Schematic description of bead motion in various glycerol–water mixtures (the darker color means higher mass fraction of glycerol in mixture); (a) 50 wt% glycerol solution, the digital pictures of a_1 and a_2 were taken at 1.2 and 2.7 h, respectively. (b) 23 wt% glycerol solution, b_1 and b_2 at 3.5 and 7.5 h, respectively. (c) 10 wt% glycerol solution, c_1 and c_2 at 0.7 and 1.4 h, respectively. The beads were obtained from Bangs Laboratories, Inc.

solution. The total time taken for entire-bead floating to the surface or sedimentation to the bottom of glycerol solutions was defined as floating or sedimentation time of beads. The accuracy of the measurements was evaluated from 5 repetitive determinations (repeatability) of the motion time of polymer beads in the same glycerol aqueous solution, and the relative standard deviations (*RSD*) were also calculated. The schematic process and digital photos are shown in Fig. 1. We have included more digital photos taken at different time in supporting information (see Fig. S1).

2.3. Characterization

The images of beads were taken using a microscope (Olympus, IX 51). Flow cytometry (Coulter, Epics XL) was utilized to measure the bead's relative size (forward light scatter, FS signal), relative granularity or internal complexity (side light scatter, SS signal). Flow cytometry was set up according to the standard operating procedure. During detection, a total of 20000 events were recorded for each time point, and the beads dispersed in water or glycerol solutions were detected at the low flow rate with a concentration of 1 mg/mL. The populations of single beads and doublet beads were

selected based on forward and side scatter. The *mean* and *RSD* of these populations were also measured. All flow cytometric data were performed using FlowJo 5.7 software (Tree Star, San Carlos, CA, USA).

3. Results and discussions

3.1. Densities and viscosities of glycerol–water mixtures

The densities of glycerol–water mixtures were measured by comparing their mass to their volume. The viscosities were calculated using the following empirical equation [10].

$$\frac{\ln v_m - \ln v_w}{\ln v_g - \ln v_w} = C_m[1 + (1 - C_m)\{a + bC_m + cC_m^2 + \cdots\}] \qquad (1)$$

where v is kinematic viscosity ($v = \mu/\rho$), μ is dynamic viscosity, ρ is the density, C_m is the mass fraction of glycerol in the mixture, and subscripts m, g and w denote the glycerol–water mixtures, glycerol and water, respectively. The constants a, b and c at 20 °C are assigned to −0.76728, 0.12153 and −1.41519, respectively. As shown in Table 1, the detected densities are close to those provided by the vendor, and the interpolated viscosities are in accordance