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Test Method

Density measurement via magnetic levitation: Linear relationship investigation

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ABSTRACT

The density of a polymer suspended in a stable state in a paramagnetic solution can be measured in magnetic levitation according to the levitation height. This method requires a complicated benchmark process prior to measurement, and the linear relationship between the density and the levitation height has not been investigated. This paper investigates the linear relationship in the magnetic levitation method, where COMSOL software was applied to simulate the magnetic field. Devices with separation distances (*d*) between 32 mm and 50 mm had high linearity ($R^2 > 0.996$). The device where d = 43 mm had the highest linearity ($R^2 = 0.99875$). Several experiments with various devices, standard glass beads and polymers were performed to validate the method. The experiments showed that this method had a high accuracy (< 0.004 g/cm^3 when d = 43 mm). The convenient measuring process enabled simple and quick density measurement for polymers in various devices with the proposed expressions and parameters. The proposed method has broad application prospects throughout density-based polymer testing.

1. Introduction

Density is a universal and effective property for polymer testing [1]. Many physical [2–6] and chemical [7,8] changes in polymers are reflected in the small differences in density. A variety of devices are currently available for measuring density, including densitometer, density-gradient columns, pycnometers and suspended microchannel resonators [9–11]. These methods are typically inconvenient, non-portable, expensive or of low accuracy when measuring small samples [12–14]. Magnetic levitation is a versatile and promising method that directly measures the density of small-sized diamagnetic samples [12]. The magneto-Archimedes method was proposed to easily achieve magnetic levitation by using a common superconducting magnet and a paramagnetic solution [15,16]. This technology was developed into the MagLev method that determined the densities of diamagnetic objects by their levitation position [12,17]. The MagLev method is used in many fields, such as quality control [3,18], diagnosis of diseases [19,20], forensic evidence [21], food analysis [17] and separation of mixtures [22–26]. Our research group proposed a horizontal magneto-Archimedes levitation configuration that enlarges the density measurement range and improves the magnetic levitation device without the limitation of a 45 mm separation distance between two magnets [27–30]. Magnetic levitation has several advantages in density measurement, as it is simple and inexpensive (requires only two permanent magnets and a tube of paramagnetic solution), has higher accuracy than other instruments, and is available for solid, powder and liquid materials [12,14,27].

Magnetic levitation configuration uses two anti-aligned permanent magnets and a paramagnetic solution to make diamagnetic objects levitate at equilibrium positions, where it is used calculate the densities by their positions [27]. Polymers are diamagnetic materials. We previously measured the density of polymers by magnetic levitation [27–30]. The measurement equation regarding the relationship between density and position was fitted by either a series of experiments with various standard density glass beads [27] or by simulation results using COMSOL, FLUENT and EDEM [28]. These methods make the benchmark process expensive or complicated to operate. The coupling between the three simulation software remains cumbersome and the simulation of the entire levitation process is complex and tedious. In the previous works, the measurement equation were fitted by a 3rd-order polynomial equation [27,28]. The linear relationship between density and position has not been systematically investigated. The complex simulation operation and the lack of systemic research on linear relationship make the magnetic levitation configuration difficult to apply.

A novel density measurement method based on magnetic levitation for polymers is proposed, where the measurement equation was fitted

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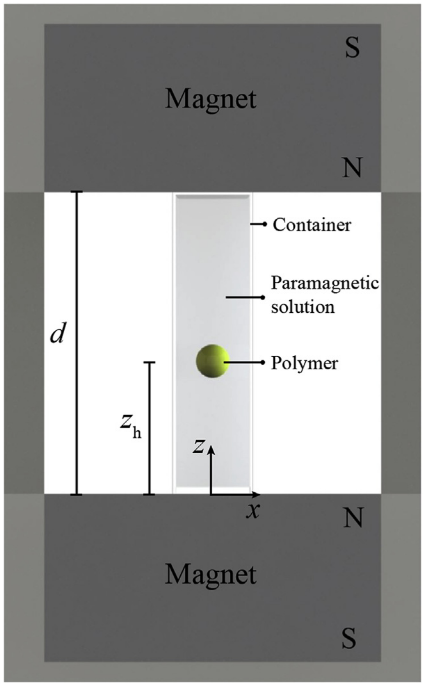

Fig. 1. Schematic diagram of the magnetic levitation device used for density measurements.

by results from a numerical simulation in COMSOL rather than experiments with standard density glass beads or simulation results for the entire levitation process. Linear fitting curves were applied to investigate the relationship between the density and the levitation height at various separation distances. A suitable range of separation distances for linear fitting was considered and verified through several experiments. A simple, and universal measurement expression is proposed for convenient density measurement of polymers.

2. Experimental methods

2.1. Measurement device

A magnetic levitation device, which was used in previous work and shown in Fig. 1, was used to measure the polymers. This device consisted of two anti-aligned magnets and a nonmagnetic container with a paramagnetic solution between the two magnets. The two rectangular N45 permanent magnets were fixed at a separation distance (d) in a plastic housing that was manufactured via 3D printing. The diamagnetic object immersed in the paramagnetic solution was forced to the equilibrium position under magnetic force and gravity. The equilibrium levitated height, z_h, of the object was captured via a photographic method [27]. This method used to measure the levitation height had a deviation less than 0.2 mm. Plastic housings with various separation distances between the two magnets were used. The magnet was 50 mm × 50 mm × 25 mm and the paramagnetic solution was a $MnCl_2$ solution.

2.2. Measurement theory

Fig. 1 defines the choice of the coordinates for density measurements by magnetic levitation (x-, y-, and z-axes; fixed to the device). In this magnetic levitation configuration, a diamagnetic object was levitated stably along the centerline in a paramagnetic solution contained in a transparent container between two permanent magnets. As seen in Fig. 1, the object – with a volume V (m^3), a density ρ_s (g/cm^3) and a magnetic susceptibility χ_s (unitless, treated as -5×10^{-6}) – immersed in solution – with density ρ_m and magnetic susceptibility χ_m – was affected by two forces: magnetic force and gravity. The magnetic force $\overrightarrow{F}_{mag}$ on the object is provided by Eq. (1) and the force of gravity $\overrightarrow{F}_{gravity}$ acting on the object is a constant provided by Eq. (2),

$$\overrightarrow{F}_{mag} = \frac{\Delta\chi V}{2\mu_0}(\overrightarrow{B}\cdot\nabla)\overrightarrow{B} \tag{1}$$

$$\overrightarrow{F}_{gravity} = \Delta\rho\overrightarrow{g}V \tag{2}$$

where $\Delta\chi = \chi_s - \chi_m$ is the difference in the magnetic susceptibility between the sample and the medium. The difference in densities is $\Delta\rho = \rho_s - \rho_m$. In these equations, $\mu_0 = 4\pi \times 10^{-7}$ N/A^2 is the magnetic permeability of free space, $\overrightarrow{B}$ is the magnetic field, ∇ represents the gradient in three dimensions, and g= 9.8 m/s^2 is the acceleration due to gravity. In this configuration, an object is levitated stably when $\overrightarrow{F}_{mag} + \overrightarrow{F}_{gravity} = 0$. The equilibrium positions were found by solving Eq. (3) for a chosen magnetic configuration. The exact analytical expression describing the magnetic field in 3D between two rectangular permanent magnets is complicated [31], so a numerical simulation of the magnetic field along the centerline between the magnets was performed to obtain the distribution of the magnetic field. We proposed a linear equation fitting the result of $(\overrightarrow{B}\cdot\nabla)\overrightarrow{B}$ along the centerline in the COMSOL. The expression for density is shown in Eq. (4), where A and C are constants for each specific magnetic levitation device according to the simulation results.

$$\frac{\Delta\chi}{2\mu_0}(\overrightarrow{B}\cdot\nabla)\overrightarrow{B} = \Delta\rho\overrightarrow{g}V \tag{3}$$

$$\rho_s = \rho_m + \frac{\Delta\chi}{2\mu_0 g}(Az_h + C) \tag{4}$$

2.3. Measurement implementation

In accordance with the measurement device and the measurement theory, there are four separate procedures for measuring the density of a PLA (polylactic acid, 2002D) particle using a d = 43 mm device and a 2.0 M $MnCl_2$ aqueous solution, as specified in Fig. 2, and are summarized in the following steps:

Step 1: A magnetic levitation device was established with particular dimensions and configuration, which included the size of magnets and the separation distance between the two anti-aligned magnets.
Step 2: The magnetic field distribution was simulated along the centerline in the device using COMSOL software. The AC/DC module of COMSOL Multiphysics 5.3 was employed to simulate the quasi-static electromagnetic field. In COMSOL, a 3D model of two anti-aligned magnets with a separation distance was created. The area out of the magnets was set as air. After setting the magnetic parameters of magnets, the distribution of magnetic field along the centerline was obtained.
Step 3: The linear fitting for the density measurement was obtained. The distribution of $(\overrightarrow{B}\cdot\nabla)\overrightarrow{B}$ along the centerline in z axis can be obtained based on the magnetic field distribution in COMSOL. A spreadsheet for the distribution of $(\overrightarrow{B}\cdot\nabla)\overrightarrow{B}$ along the centerline was exported by COMSOL. A linear fitting and the constants A and C in Eq. (4) were obtained by using these values.
Step 4: The linear fitting equation between ρ_s and z_h was generated, as shown in Eq. (4). For a polymer levitated with this magnetic configuration, the density ρ_s was calculated by the levitation height z_h using Eq. (4).

3. Results and discussion

Four case studies were performed to validate the simulation-based