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Test Method

Enlarging density measurement range for polymers by horizontal magneto-Archimedes levitation

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ABSTRACT

To overcome the major limitation of magnetic levitation, narrow density measurement range, a novel horizontal magneto-Archimedes levitation method is proposed for enlarging density measurement range of polymers. This method provides a new way to tune the components of the gravitational force relative to the magnetic field, which enhances the effect of magnetic force acting on the polymers. Experiments with different diamagnetic materials, different paramagnetic solutions, different sized polymers and various polymers were carried out to verify the proposed method. Experimental results show that the method enlarges density measurement range from 1.007–1.483 g/cm^3 to 1.244–14.914 g/cm^3 (depending on the 2.5 M $MnCl_2$ aqueous solution), and it enables density measurements to be performed for high-density polymers (e.g., Teflon and BMC) and other diamagnetic materials (e.g., Brass, barium sulfate and aluminum). In general, the proposed method has wider measurement range, high-accuracy, simplicity-of-use and low-cost, and it has prospects of broad application in characterizing high-density polymers and polymeric composites.

1. Introduction

Density is a simple but effective quality criterion in diagnosing polymers [1]. Internal defects [2–4], physical [5–8] and chemical [9] changes in polymers would induce density variations, and hence density measurements have a significant position due to their frequent usage in both the laboratory and the factory [1]. Current density measurements (such as densitometer [10], density-gradient columns [11] and ultrasonics [12]) are usually inconvenient, expensive and of low accuracy, especially for small-sized samples [13]. Magneto-Archimedes levitation is a novel and promising method for density measurement [14–17]. G.M. Whitesides et al. developed a magnetic levitation device (named MagLev) [18] to determine the densities of diamagnetic objects, such as biomolecules [19], forensic evidence [20] and foods [21]. Our research group proposed an improved magneto-Archimedes levitation device for measuring polymer density, which broke the limitation of the 45 mm separation distance between two magnets [22,23]. In general, the magneto-Archimedes levitation has several advantages in density measurement. (1) It has high accuracy, which can distinguish atomic-level differences in the chemical compositions of materials [24]. (2) It is a versatile method to directly measure the density of solid, powder or liquid diamagnetic materials with arbitrary shape [20,21]. (3) It is simple, convenient and inexpensive, requiring only two permanent magnets with like-poles facing each other and a tube of paramagnetic solution [25].

Despite these advantages, there is a major limitation: density measurement range is narrow and close to the paramagnetic solution density [18]. Because of the restriction of paramagnetic salts' solubility, most of experiments were performed using a 2.5 M $MnCl_2$ aqueous solution, which results in a density measurement range from 1.007 g/cm^3 to 1.483 g/cm^3 [18,23]. This range does not cover high-density polymers, such as Teflon [26,27], BMC (bulk molding compound) [28,29] and polymer-metal composites [30]. Therefore, a magneto-Archimedes levitation method with a larger density measurement range for polymers is highly desirable. A. Nemiroski et al. presented a tilted magnetic levitation device (named tilted MagLev), which enabled a complete density measurement range for diamagnetic objects [31]. The influence of container wall friction makes the tilted MagLev difficult to operate, i.e., aqueous dextran is needed to increase paramagnetic solution viscosity together with a container rotation operation to overcome the static friction from physical contact with the wall of the container.

Here, a novel horizontal magneto-Archimedes levitation method is proposed for enlarging the density measurement range of polymers in which the mathematic relationship between the density and the levitated position is established. This method provides a unique way to

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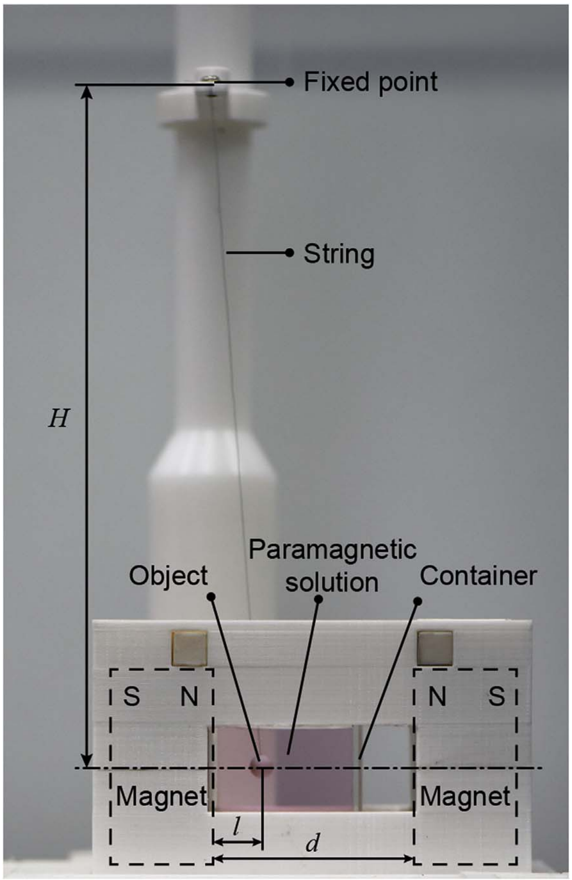

Fig. 1. Photograph of the horizontal magneto-Archimedes levitation device for measuring the density of a diamagnetic object.

tune the components of the gravitational force relative to the magnetic field, which enhances the effect of magnetic force acting on the polymers. Experiments with different diamagnetic materials, different paramagnetic solutions, different sized polymers and various polymers were carried out to verify the proposed method.

2. Experimental methods

2.1. Measurement device

A horizontal magneto-Archimedes levitation device for measuring the density of a diamagnetic object is shown in Fig. 1. The device includes two permanent magnets, a container of paramagnetic solution and a plastic shelf with a string. The container of solution (e.g., $MnCl_2$ aqueous or methanol solutions) is placed between two horizontal anti-aligned magnets with like-poles facing each other. A plastic housing was three-dimensional printed to mount the two magnets. The string is fastened at a fixed point, which is directly above the right surface of the left magnet, and the other end of the string is adhered to a diamagnetic object. The diamagnetic object immersed in the paramagnetic solution is forced towards the right magnet under the action of magnetic force. When the object is levitated in a stable state, its density can be calculated through its levitated position (l), as shown in Fig. 1. The levitated position is captured by a photographic method [17,22,23], and can be calculated using Eq. (1),

$$l = \frac{N_1}{N_d} \times d \tag{1}$$

where d is the distance between two magnets, N_1 is the number of pixels between the object and the left magnet, and N_d is the pixels along the centerline between two magnets.

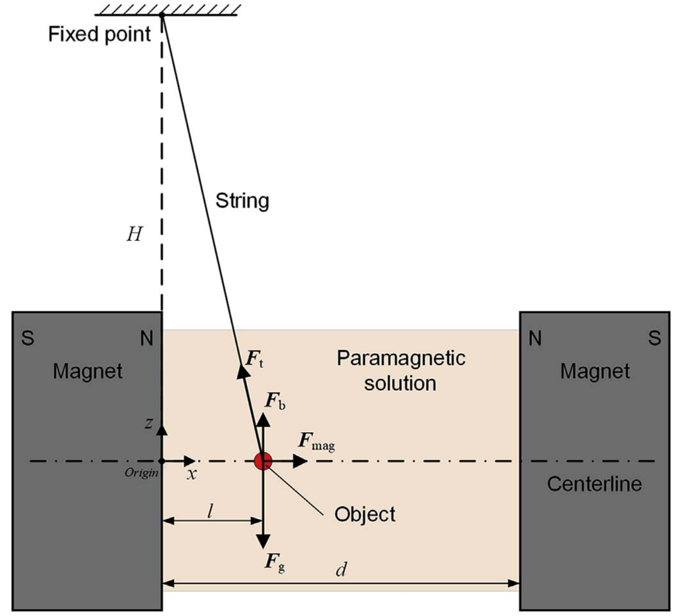

Fig. 2. Schematic diagram of the horizontal magneto-Archimedes levitation device for density measurement.

2.2. Measurement theory

In the horizontal magneto-Archimedes levitation device, as shown in Fig. 2, the origin of coordinates is set at the center of the right surface of the left magnet. The diamagnetic object immersed in the paramagnetic solution is affected by the resultant force of the gravity $\overrightarrow{F_g}$ (Eq. (2)), the buoyancy $\overrightarrow{F_b}$ (Eq. (3)), the magnetic buoyancy caused by the magnetic field $\overrightarrow{F_{mag}}$ (Eq. (4)), and the pulling force of the string $\overrightarrow{F_t}$. As the object is levitated at the centerline of two magnets, the magnetic force $\overrightarrow{F_{mag}}$ is from left to right in the direction of the arrow, as Fig. 2. When the resultant force of $\overrightarrow{F_g}$, $\overrightarrow{F_b}$, $\overrightarrow{F_{mag}}$, and $\overrightarrow{F_t}$ meets Eq. (5), the object will be levitated at an equilibrium position.

$$\overrightarrow{F_g} = \rho_s \vec{g} V \tag{2}$$

$$\overrightarrow{F_b} = -\rho_m \vec{g} V \tag{3}$$

$$\overrightarrow{F_{mag}} = \frac{\chi_s - \chi_m}{\mu_0} V (\vec{B} \cdot \vec{\nabla}) \vec{B} \tag{4}$$

$$\overrightarrow{F_g} + \overrightarrow{F_b} + \overrightarrow{F_{mag}} + \overrightarrow{F_t} = 0 \tag{5}$$

where ρ denotes density, χ represents magnetic susceptibility. The subscripts s and m refer to the object and the paramagnetic solution, respectively. Parameter V is the volume of the object, $\vec{g}$ is the acceleration of gravity, $\vec{B}$ is the vector of magnetic field strength, and μ_0 is the permeability of free space, which is $4\pi \times 10^{-7}$ N·A^{-2}. According to the force balance of the levitated polymer, the calculation formula for the density of the object is derived in Eq. (6).

$$\rho_s = \rho_m + \frac{H(\chi_s - \chi_m)}{lg\mu_0}\left(B_x\frac{\partial B_x}{x} + B_y\frac{\partial B_x}{y} + B_z\frac{\partial B_x}{z}\right) \tag{6}$$

Our research group employed a 3rd-order polynomial equation to fit the distribution of $\left(B_x\frac{\partial B_x}{x} + B_y\frac{\partial B_x}{y} + B_z\frac{\partial B_x}{z}\right)$ along the centerline of magnets (50 mm × 50 mm × 25 mm) in a magneto-Archimedes levitation configuration with a separation distance of 60 mm [23]. Therefore, Eq. (6) can be simplified as a 3rd-order polynomial equation, as shown in Eq. (7),