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The Influences of Optical Forces on the Lattice Structure of Electrorheological Suspensions

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Abstract: In order to investigate the influences of the optical forces on the lattice structure of an electrorheological (ER) suspension, on the basis of the experiment of Michael M. Burns etal., comparing their sample with an Electrorheological suspension, this paper substantially discusses the influences of intense light beams on the interaction between the dielectric particles immersed in electrorheological suspensions (ER). It respectively calculates out the optical forces exerted either on the polystyrene spheres in the sample of Michael M. Burns etal. Or on the corn-starch spheres in an ER suspension, the calculation results of this paper show that increasing the intensities of the incident laser beams or the gradient of the applied electric field can generate stronger optical forces acting on the spherical dielectric particles in an ER fluid than acting on those spheres with nearly the same mass and figuration in the suspension sample of Michael M. Burns etal.. Similar to the experimental result of Michael M. Burns et al., when increasing the intensities of the incident laser beams or the gradient of the electric field up to a critical value, it will give rise to the optical crystallization and optical binding of ER suspensions.

Keywords: Dielectric Particles, Oscillator, Optical Forces, Optical Standing Wave Fields, Optical Crystallization, Lattice Structure

1. Introduction

Increasing an applied electric field up to a critical value will result in all of the particles in the solvent of electrorheological (ER) suspensions rearranged nearly parallel to the direction of the applied electric field, with columns or fibers of particles, the ER fluids will undergo the liquid continuous phase and the dispersed phase [1-6]. A lot of researchers have focused the exciting interests on diverse strange properties of ER fluids due to their important applications in industries, such as shock absorbers, clutches, or valves, and so on. Experimenters observed the phenomenon of ER effects occurring in fluid suspensions begun in 1939[1], however, the theories of describing the phenomenon have not been satisfactorily established, in fact, certain experimental observations could not be explained by the preliminary theories [5, 7].

Determining the lattice structure of induced ER solidification is one of the early works in this field, some researchers performed a series of experiments by use of the technology of laser diffraction, and observed that the lattice structure of electric field-induced ER solid shows the bct lattice [8-9]. Nevertheless, the bct lattice is not consistent with the theoretical analysis of T. C. Halsey and W. Toor [5]. Moreover, some other experimenters did not observe the bct lattice of electric- induced ER solid in their experiments [10].

Since A. Ashkin et al. Experimentally demonstrated that the gradients of time averaged optical fields generate static forces on the microscopic dielectric particles in suspensions [11-12], the optical matters arising from the optical crystallization and the optical binding have been extensively studied [13-15]. The influence of optical forces evidently differs from the ER effects, but it can also produce the periodic structure of the dielectric particles in suspensions, and merits the interest of discussions of this paper.

2. Optical Standing WaveFields

Using the technology of laser diffraction, Michael M. Burns etal. Demonstrated the phenomenon of optical crystallization of a colloidal suspension which is composed of micrometer-sized polystyrene spheres and water. The apparatus of their experiment is schematically illustrated in Figure 1 [16].

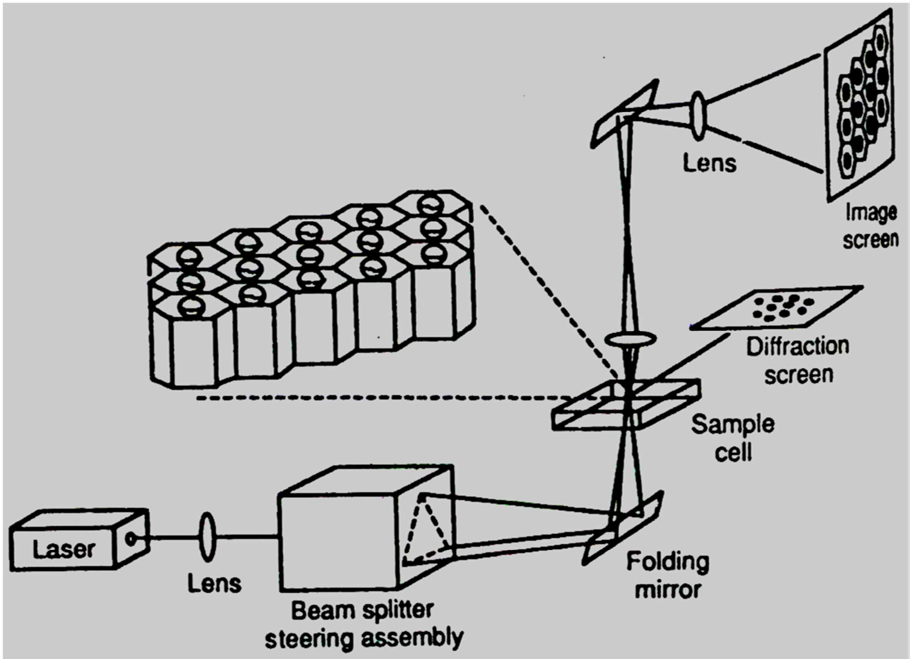

Figure 1. *Experimental set up for optical crystallization experiments.*

In the experiment, the light source is an Argon ion laser which supplies the light with a wavelength of 5145 Å and the power of merely 10W, the light beam is split and formed into three equiangular incident beams to converge on the cell, but the appropriate of their intensities, polarizations, focal properties, and mutual phases are required in order to generate the optical standing wave fields in the sample.

With the incident beams radiating on the surfaces of spheres, merely after a period of a few seconds the experimenters observed that all of the polystyrene spheres are lifted from the bottom to the top of the cell, and the original structure of the colloidal suspension becomes a new periodic structure, it is a lattice structure of the optical matter.

However, their experimental sample is quite different from an ER suspension in the ratio of ε_p (the particle permittivity) to ε_f (the fluid permittivity), for example, in consideration of an ER suspension which is composed of the corn-starch microscopic particles and the mineral oil, $\varepsilon_f = 2.2$, and $\varepsilon_p \approx 2.67$, the permittivity ratio is approximately equal to 1.214. Unlike ordinary solvents of ER suspensions, although the value of dielectric permittivity of the polystyrene spheres ε_p may be merely in range of 2.5～2.7 at the room temperature, water has the dielectric permittivity $\varepsilon_f = 61.5$ at the temperature of 20°C; so the ratio is nearly 28 times of that of the ER suspension.

For some technical reasons, we have not yet been able to repeat the experiment of Michael M. Burns et al. With an ER sample, therefore, the present discussion on the effects of the optical forces will restrict to the theoretical analyses by means of their experiment. If the sample is substituted with an ER suspension consisting of the corn-starch spheres and mineral oil whose indices of refraction are respectively 1.634 and 1.4832, the index of refraction in the suspension can periodically alternate from high to low, to serve as the dielectric mirrors of generating the optical standing wave fields [17].

In general, there are two ways to achieve the new ordered structure, in the first, by directly applying the external optical standing wave fields; in the second, using the external intense light beams to induce the interaction forces between dielectric particles and trap them in a new state.

3. Optical Forces

When the intense light beams radiate on the microscopic dielectric particles, they will be polarized under the electro-magnetic fields, and generate the charge density $\rho(t)$ and current density $j(t)$ which vary as sympathetically oscillating functions of cosine with time t, therefore, an appropriate description about the interaction of the two neighboring dielectric particles is to recognize them as two interacting oscillators with a distance r apart, either of them consists of a light particle of mass m and charge e, and harmonically with the resonant frequency ω_0 bound in a heavy mass of opposite charge [18].

The intense lights radiating on the oscillators results in scattered fields, the scattered fields arising from one oscillator generate the mutual forces acting on its neighbor particles. There are two types of forces dominating the interaction between the oscillators, the first arises from the dipole moment of one oscillator acted on by the gradient of the scattered electric field from the other oscillator; in the second, the Ampere force which is generated by the induced currents in the two oscillators. In case of $\vec{E}$ perpendicular to the direction of connecting the two oscillators, and the electric field vector $\vec{E}\times\vec{r}$ perpendicular to the wave vector $\vec{k}$ ($|\vec{k}| = \omega/c$), it can be found from solving the coupled classical Maxwell-Lorentz equations that the interaction energy of the dipole oscillators is written [18]

$$W = -\frac{1}{2}\alpha^2E^2k^2\cos(kr)/r, \qquad (1)$$

Where $kr \geq 2\pi$, $\alpha = e^2/m(\omega_0^2-\omega^2)$ is the polarizability of the oscillator at the optical frequency ω, the binding occurs at $kr \approx 2m\pi(r \approx m\lambda)$ when the value of W approaches the minimum, m is an integer, λ notes the wavelength.

Eq.(1) contains the harmonic time dependence of the incident electric field, the static (or time-average) optical force which will give rise to optical binding over a cycle of the electromagnetic field is given by [16]

$$\vec{F} = -\nabla W = \frac{1}{2}\alpha\nabla E^2. \qquad (2)$$

If the two oscillators are realized as two dielectric spheres with radius a and relative index of refraction n, the polarizability of binding is conveniently estimated by [18]

$$\alpha = a^3(n^2-1)/(n^2+2)\ (ak < 1). \qquad (3)$$

For example, considering the sample of Michael M. Burns et al., the relative index of refraction of polystyrene spheres in water is 1.2[18], in terms of eq.(3)

$$\alpha_1 = a^3(1.2^2-1)/(1.2^2+2) \approx 0.128a^3. \qquad (4)$$

Similarly, if the corn-starch spheres with the same radius a immersed in mineral oil, the relative index of refraction is about 1.102, thus,

$$\alpha_2 = a^3(1.102^2-1)/(1.102^2+2)/ \approx 0.0667a^3. \qquad (5)$$

$\alpha_1 \approx 1.919\alpha_2$. Using $\vec{F_1} = \frac{1}{2}\alpha_1\nabla {E_1}^2$ and $\vec{F_2} = \frac{1}{2}\alpha_2\nabla {E_2}^2$ respectively represent the optical forces exerted on the polystyrene spheres and the corn-starch spheres, it is clear from eq.(2) that if increasing the intensities of the incident light to make the value of $\nabla {E_2}^2$ approximately up to the value of $2\nabla {E_1}^2$, the value of $|\vec{F_2}|$ will overpass that of $|\vec{F_1}|$ although these two type spheres are slightly different in mass and the resistant. When the value of $|\vec{F_2}|$ dominate all other forces in the ER suspension, such as the viscous force et al., just like the experimental result of Michael M. Burns et al., the corn-starch spheres will be "trapped" in a new state, rearranged, and undoubtedly show a new periodic lattice of the photonic crystal.

4. Conclusions

Michael M. Burns et al. experimentally demonstrated that the intense light beams radiating on microscopic particles immersed in water can generate the optical force which is quite different from those arising from electrons in ordinary matters. If their sample is replaced by an ER suspension which is composed of the corn-starch spheres and mineral oil, the polarizability of binding for these two samples are respectively calculated out by eq.(4) and eq.(5), therefore, it is clear from eq. (2) that if increasing the intensities of the incident light to a critical value to make the value of $\nabla {E_2}^2$ approximately up to the value of $2\nabla {E_1}^2$ and the value of $|\vec{F_2}|$ dominate all other forces in the ER suspension, the ER suspension will similarly achieve the effects of optical crystallization and optical binding.

Because the intense light beams radiating on the dielectric particles is different from an external electric field exerted on the ER suspension in experiments, therefore, the influence of optical forces on those particles is not equivalent to the ER effects. Moreover, since the intense light beams can serve as to rearrange dielectric particles in suspensions, so in the experiment of using the technology of laser diffraction to observe the lattice structure of an ER suspension [8-9], the influences of the optical forces must be carefully considered.

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