Frequency dependence of a field-induced force between two high dielectric spheres in various fluid media

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(Received 8 July 2003; accepted 23 September 2003)

The frequency dependence of the interaction force f between two identical $SrTiO_3$ spheres has been investigated in various carrying media with different dielectric constants under ac electric field strengths E_0. We note that the force f is proportional to E_0^2 and increases with the frequency regardless of the carrying media. The force however, is found to be stronger than that expected theoretically when the interspherical gap is small. The experimental results demonstrate that it is the conductivity that dominates the interaction force at low frequency, while dielectric polarization becomes more important at high frequency, and reveal that stronger interaction force between high dielectric spheres may be obtained in higher dielectric fluids when the frequency of the ac field is high enough. Some anomalous behaviors of f versus frequency are found when the two spheres are nearly touched. [DOI: 10.1063/1.1626804]

I. INTRODUCTION

One of the key issues in obtaining a promising electrorheological (ER) fluid is finding a compatible fluid medium in which the fine particles can be suspended freely. Earlier experimental work on Zeolite (+water)/oil ER fluids showed that the permittivity of the oil could strongly influence the quasistatic yield stress under dc electric fields.[1] In another investigation, Atten *et al.* proposed a conducting model and directly measured the interaction force between two hemispheres surrounded by media of air and a conductivity-controllable mineral oil.[2] The influence of the liquid-phase properties of ER fluids on the interaction among the solid particles under an ac electric field has yet to be investigated. Even though some theoretical works have been done in the last decades,[3–9] the force induced by electric fields between particles, especially under the ac electric field, has not yet been precisely determined experimentally.[10,11] Most previous experiments were performed based on ER fluids subjected to dc and low-frequency electric fields. Davis[5,12,13] ever analyzed the effect of conductivity in ER fluids and predicted the performance of a metal-particle/insulating oil system at high frequency, which was demonstrated experimentally by Inoue.[14] In our previous work, we measured bispherical interactions in nitrogen gas under an ac electric field and found that the interaction force f between two spheres followed a well-known quadratic dependence on the field strength E_0, i.e., $f \sim E_0^2$.[15] In this work, we report our experimental studies on the frequency dependence of the interaction between two identical dielectric spheres immersed in different media.

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II. EXPERIMENT

Slightly different from our previous measurement of two spheres in a gas medium,[15] the current experimental setup has been modified for a liquid medium as can be seen in the inset of Fig. 1, where two horizontally fixed copper plates (160.0 mm in diameter) separated by a gap of 49.1 mm by Teflon props are placed in a transparent round glass vat filled with a certain kind of fluid medium. The wires linked to the two electrodes are insulated with quartz tubes for the protection from the short circuit in the liquids. The vat is mounted on a platform used to adjust the spacing δ between the two spheres, which are made of single crystalline $SrTiO_3$ ($\varepsilon = 249$) of 6.30 ± 0.01 mm in diameter, with an accuracy of 0.001 mm by a computer-controlled elevator. With the aid of two thin Al_2O_3 insulating tubes, the two spheres are precisely arranged in the center regime of the two plates, with their vertical axis parallel to the applied electric field. The attractive force between two spheres is measured with an electronic balance (sensitivity of 0.001 g). The whole apparatus is sealed in a plexiglass box for protection from moisture and dust.

III. RESULTS AND DISCUSSION

The spacing and field strength dependences of the interaction forces between the two identical single crystalline $SrTiO_3$ spheres in silicone oil (dielectric constant $\varepsilon = 2.54$) were determined. The interaction force f as a function of field strength E_0, between two $SrTiO_3$ spheres in silicone oil, measured at different interspherical gaps is shown in Fig. 1, where the electric field frequency is fixed to be 50 Hz and the gap between the two spheres is adjusted from 0.005 to 0.7 mm. In Fig. 1, we see that the interaction force increases as the field strength increases and satisfies the relationship $f \sim E_0^2$ as is expected. The normalized values of f/E_0^2 vs δ,

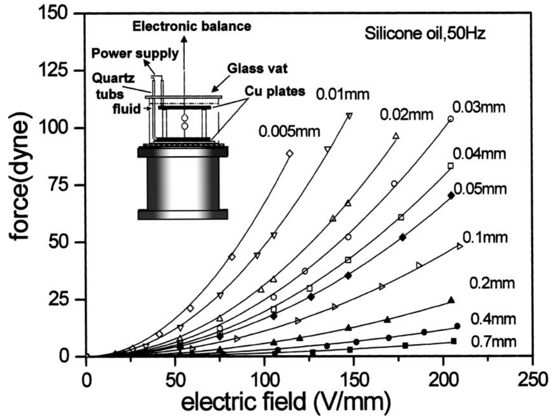

FIG. 1. Attractive forces between two identical spheres of $SrTiO_3$ in silicone oil at gap spacing δ (0.005–0.700 mm) vs the applied electric field. Inset shows the apparatus for the experiment.

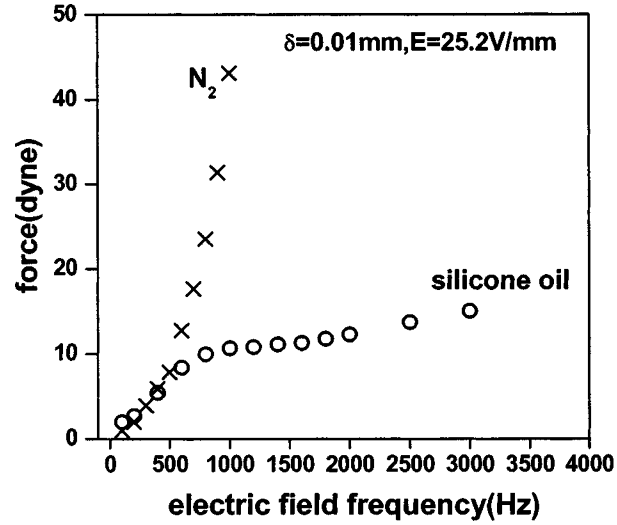

FIG. 3. Frequency dependence of the interaction between two identical $SrTiO_3$ spheres with the gap spacing $\delta = 0.01$ mm, in N_2 and in silicone oil, respectively.

compared with the calculations, are plotted in Fig. 2, which shows similar behavior to our previous observations in nitrogen gas medium.[15] These results indicate again that all three models for the calculations are no longer valid whether liquids or gas as the medium phase for the case of a very thin gap.

For a small spacing ($\delta = 0.01$ mm), the measured frequency dependencies of the interactions between two $SrTiO_3$ spheres in N_2 and silicone oil are shown in Fig. 3, respectively. It can be seen that the force f is about the same in N_2 and silicone oil when the frequency is lower than 600 Hz and f increases much rapidly in the N_2 medium than that in silicone oil with the frequency further increasing. However, as the gap becomes wider, the anomalous difference disappears as seen in Fig. 5, in which the gap is 0.10 and 0.30 mm, respectively. It is shown that, with same field strength and gap, f is much stronger when the two spheres immersed in the silicone oil than in the nitrogen gas. The reason, that the behavior of the force versus frequency depends on the spacing of two spheres, is still not clear at the moment. From Figs. 3 and 4 we only know that the interaction force of two high dielectric spheres increases with the frequency increasing no matter what media is used.

Further experiments were carried out with various liquids as the media. Four kinds of liquids with different dielectric constants: castor oil ($\varepsilon = 4.20.$), ethyl benzoate ($\varepsilon = 5.45$), ethyl salicylate ($\varepsilon = 8.65$), and methyl salicylate ($\varepsilon = 9.46$) were employed. The measured f versus the field frequency is compared with that in silicon oil. They are shown in Figs. 5(a) and 5(b), where $\delta = 0.01$ mm and $E_0 = 25.2$ V/mm. In Fig. 5(a), The result, that the interaction in castor oil is stronger than that in silicone oil as the frequency changes from 100 Hz to 3 kHz, must be due to the higher dielectric constant ε_m of the castor oil according to $f \sim \varepsilon_m$.[8,12,16] Here, the conductivity σ_m of silicone oil and castor oil ($\sim 10^{-13}\ \mathrm{s\,m^{-1}}$) are on the same quantitative scale while the dielectric constant of $SrTiO_3$ is much higher in the system, leading to the mismatch factor $\beta^2 \rightarrow 1$ regardless of the variation of frequency.

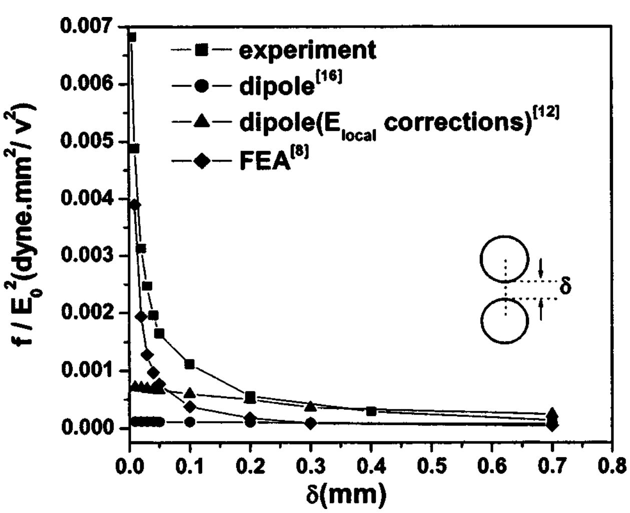

FIG. 2. Comparison between the experimental results and theoretical calculations.

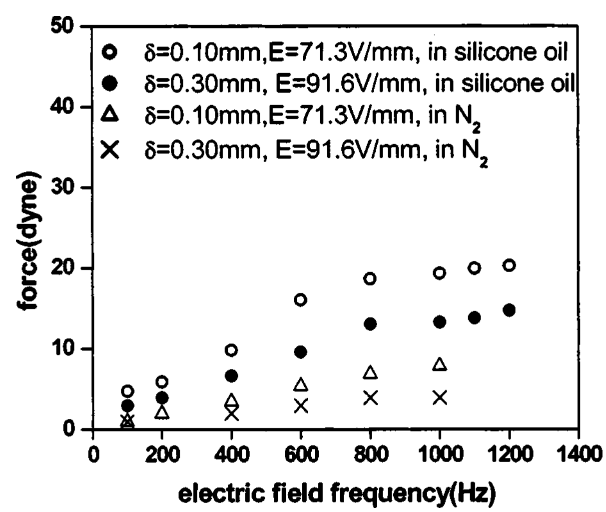

FIG. 4. Frequency dependence of the interspherical force with the gap spacing δ (0.10 and 0.30 mm) in N_2 and in silicone oil, respectively.

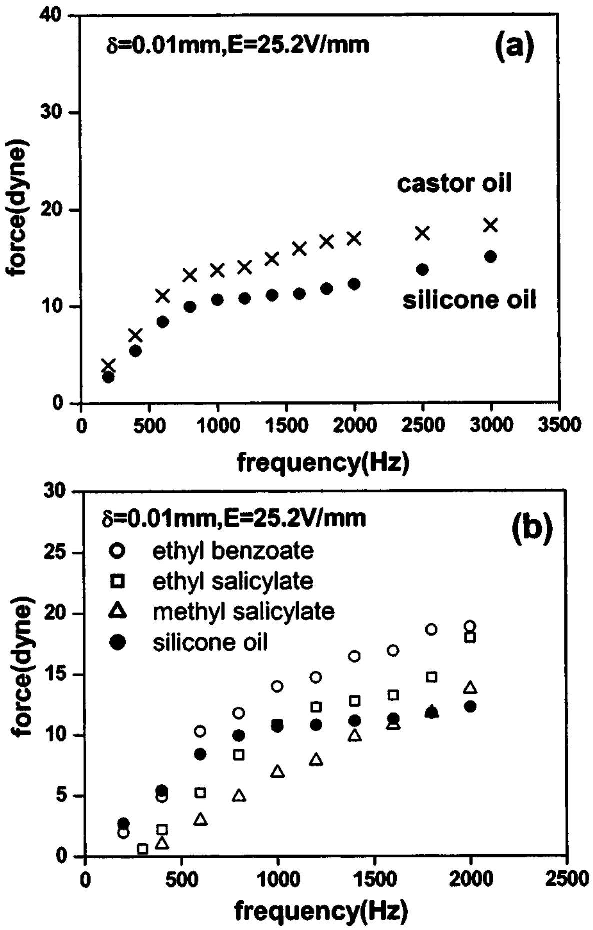

FIG. 5. Frequency dependence of the force between two spheres of $SrTiO_3$, in various fluid media: (a) castor oil and silicone oil; (b) ethyl benzoate, ethyl salicylate, methyl salicylate, and silicone oil, respectively.

In order for the conductivity σ and the dielectric constant from high to low, there are methyl salicylate ($\sigma=6\times10^{-7}$ s/m), ethyl salicylate ($\sigma=1\times10^{-7}$ s/m), ethyl benzoate ($\sigma=5\times10^{-8}$ s/m), and silicone oil ($\sigma\sim10^{-13}$) to be used as fluid media. This fact must result in the distinct frequency dependence of the attractive force of $SrTiO_3$ ($\sigma=2\times10^{-8}$) spheres in different fluids as shown in Fig. 5(b). We note that the force f in the silicone oil is the strongest while that in the methyl salicylate is weakest when the frequency is lower than 400 Hz. However, f in ethyl benzoate is higher than that in silicone oil at about 500 Hz. When the frequency continuous to rise, the crossover points can be seen at frequencies of 1000 and 1800 Hz for ethyl salicylate and methyl salicylate, respectively. These results demonstrate that dielectric polarization governs the behavior of the interaction at the high frequency and dc conduction plays a main role in the low frequency regime and thus imply that the higher dielectric constant of the fluid medium must contribute a stronger interaction force when the field frequency is high enough. The complex relation of the force versus the frequency for different fluids at low frequency is attributed to the conductivity ratio between solid and liquid, which is small in our case except silicon oil.

IV. SUMMARY

In conclusion, the electric field frequency dependence of interaction force f between two identical high dielectric spheres of $SrTiO_3$ in different media has been measured with various interspherical spacings. For the case of a very thin spacing, an obvious difference on frequency dependence exists between liquid and gas medium in the high frequency region and the theoretical calculations are no longer valid to explain the experimental results. The relation of f and frequency depends on the mismatch of the conductivity and dielectric constant between sphere and liquid when the spacing is not very small. The conduction and dielectric mismatch dominate the behavior of low frequency and high frequency respectively. In higher dielectric fluids stronger interaction force between high dielectric spheres may be obtained when the frequency of the ac field is high enough.

ACKNOWLEDGMENTS

The authors would like to thank Peng Zheng, Su Zhibin, Men Shouqiang, and Xu Xiaoyu for their preliminary work on this research and Professor Sun Gang and Professor Hou Meiying for useful discussions. This work is supported by the National Science Natural Foundation of China, Nos. 10029401 and RGC HKUST 6154/01P.

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