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Experimental and numerical investigations on the separation behavior of magnetic particles under an alternating gradient magnetic field

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Background

Separation of microparticles is of great importance for biological and chemical applications, such as cell sorting, DNA purification and biocatalysis, with the development of microfabrication and lab-on-a-chip technologies. Among the separation methods, the magnetophoretic separation by the use of magnetic fields has attracted a growing interest due to the characteristics of simple, non-invasive and ionic concentration. However, the aggregation behavior of magnetic particles under an externally applied magnetic field will give rise to these problems: Non-target bodies are entrapped in aggregates; Agglomerates lead to channel blockage in separation systems; Aggregation of particles of different sizes could result in ineffective separation. Therefore, high-precision separation studies are limited to be carried out only at lower concentration condition.

Objectives

- ❖ An alternating gradient magnetic field could be applied to solve the aggregation problem of multiple types of particles with different sizes in separation process.
- ❖ This is based on the fact that the interparticle interaction force changes with the external field direction.

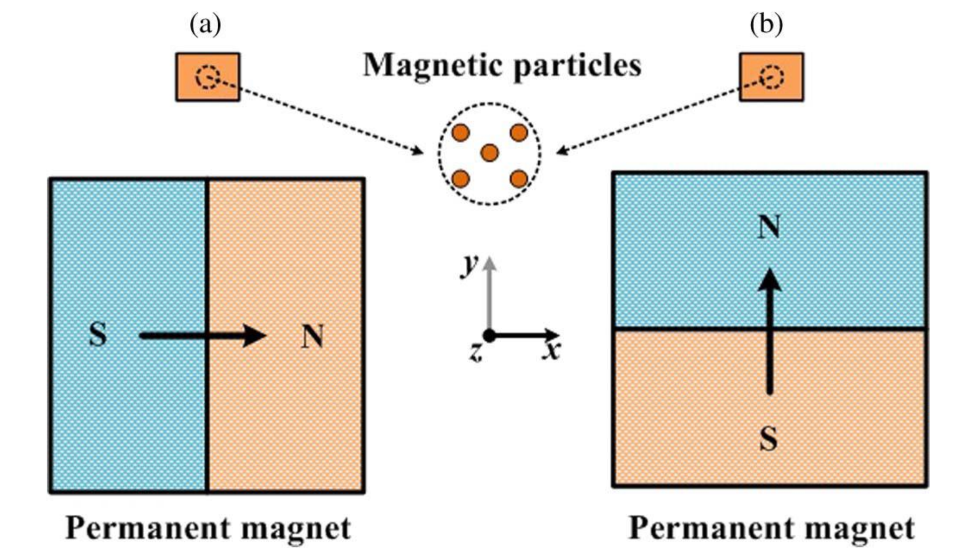


Fig. 2 Schematic diagram of two types of gradient magnetic field with different directions. (a) The horizontal direction, (b)the vertical direction.

Visualization of aggregation

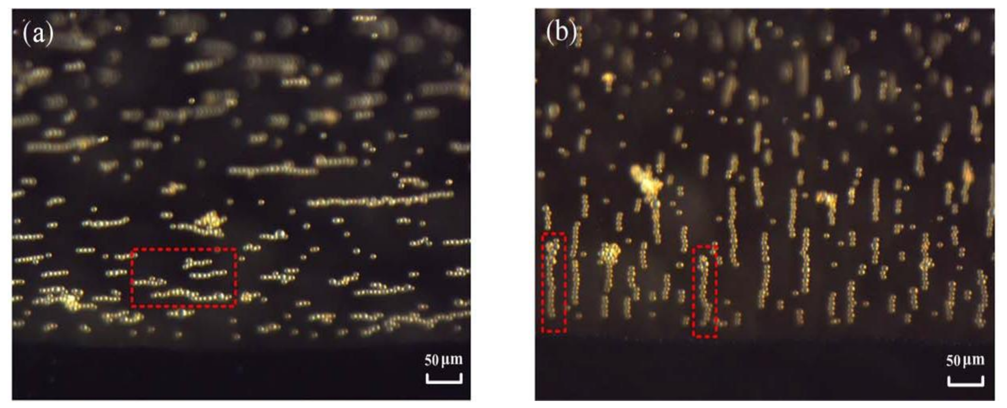


Fig. 3. Aggregation behavior of magnetic particles under the action of the system in (a) Fig.2(a), (b) Fig.2(b).

Analysis and Method

Why exists aggregation?

The magnetic torque and force generated by the interactions between magnetized particles:

$$E_{ij}{}^{M} = \frac{\mu_0 m_i m_j}{4\pi r_{ij}{}^3}\{n_i \cdot n_j - 3(n_i \cdot t_{ij})(n_j \cdot t_{ij})\}$$

$$F_{pp} = -\nabla(E_{ij}{}^{M})$$

F_r along the linking line of the two particles is negative when the angle θ is less than 54.73° , which means that there is a magnetic attraction force between the particles. The force F_θ is positive which means the particle m_2 will move in a counterclockwise direction, as shown in Fig. 1(c).

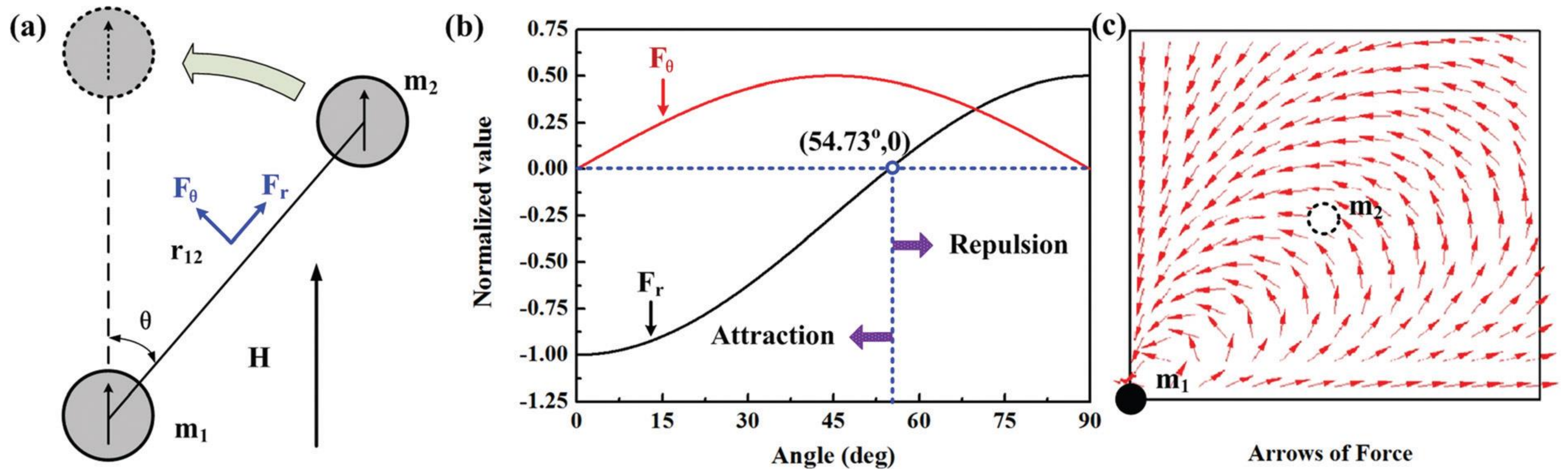


Fig.1. The interaction forces of magnetic particles in the two-dipole system. (a) The physical model, (b) the relationship between the interaction forces and the angle θ and (c) the arrows of the interaction forces. The angle θ means the angle between the linking line of the two particles and the direction of magnetic field.

Setup to prevent aggregation

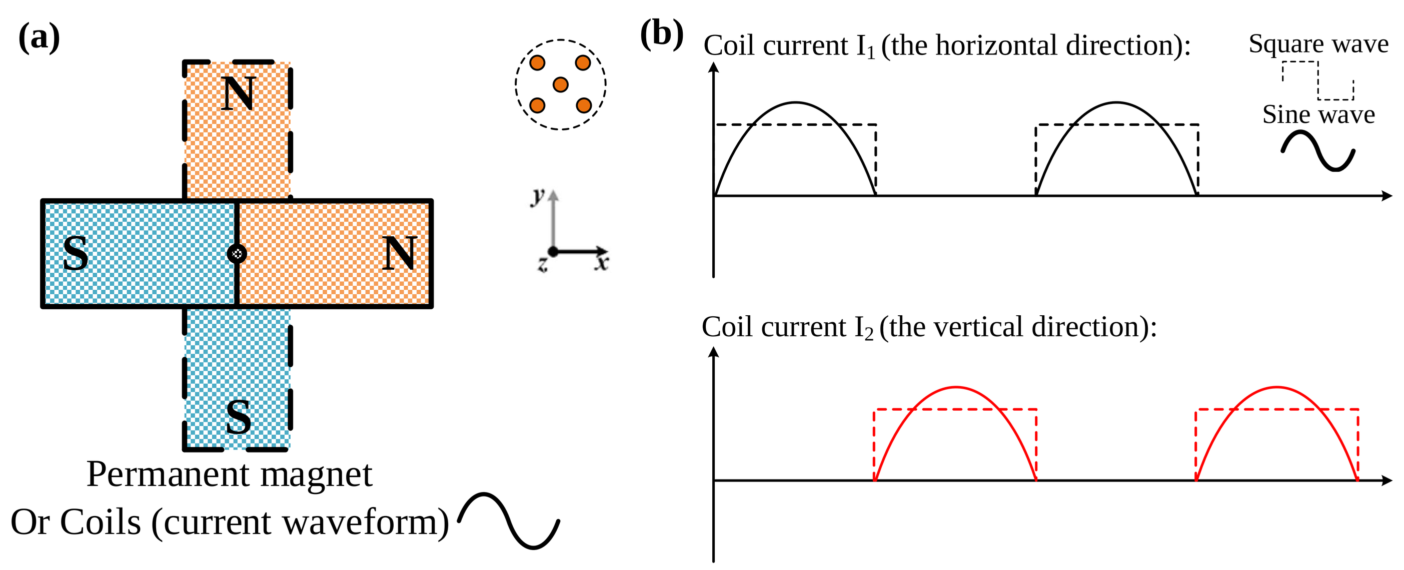
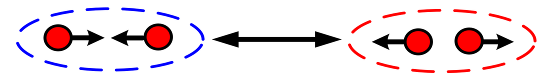


Fig. 4 (a) Schematic diagram of two configurations of alternating gradient magnetic field, (b) The time-varing currents flowing in the coils.

Two coils or one external adjustable permanent magnet were used to generate an alternating gradient magnetic field. The gradient magnetic field distribution in the region of interest could be changed by adjusting the direction of currents flowing in the coils, or changing the direction of placement of permanent magnet periodically. The current waveform could be sine wave or square wave.

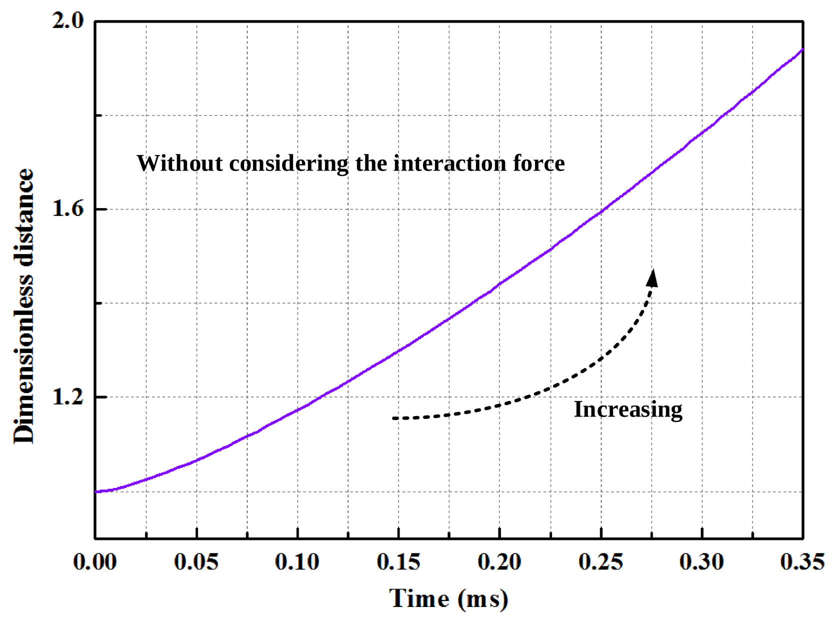
Thus, intermittent repelling forces acting on the particles lead to the disaggregation of clusters for better separation.



Alternating attraction and repulsion forces

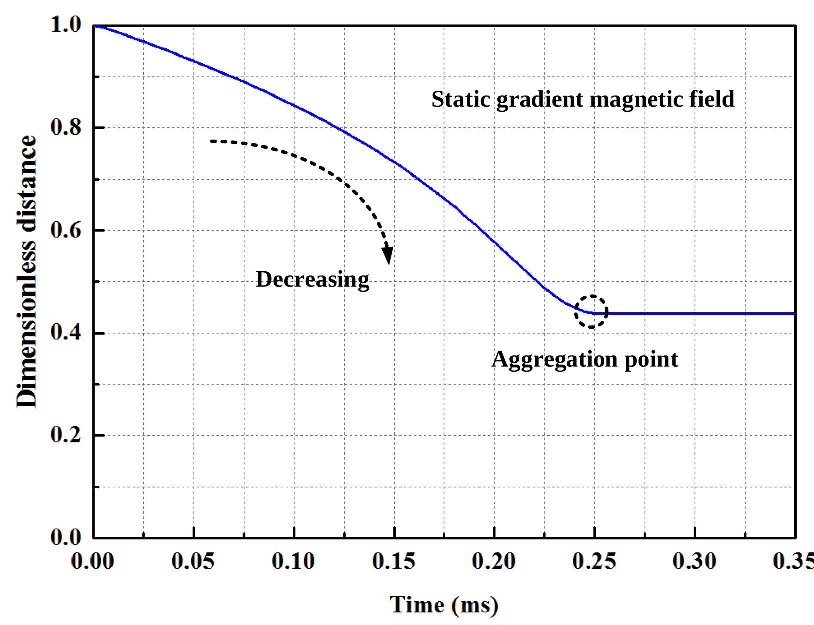
Results and Discussion

Simulation Validation



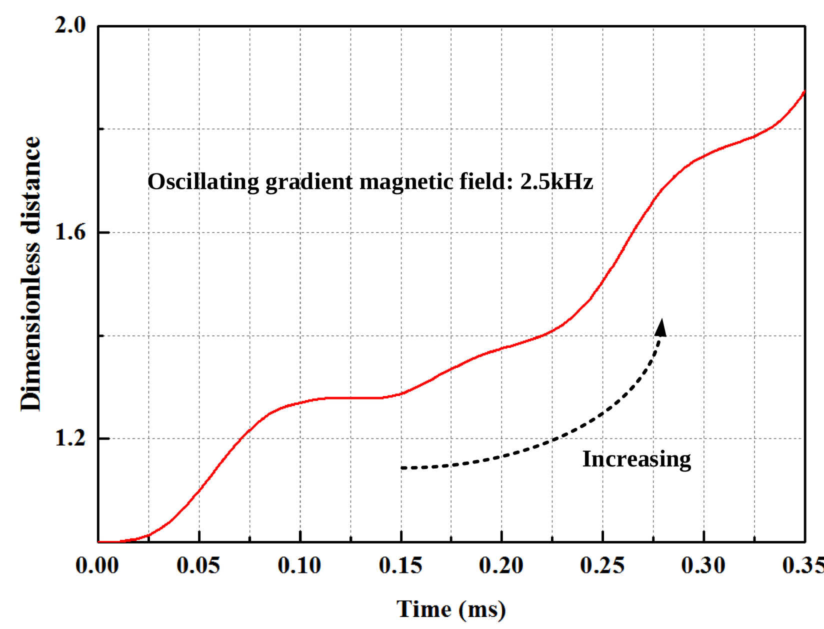
1. Assume that the distance between particle m1 and m2 is far enough, or ignoring the interaction force F_r, the two particles are moving farther away and will never collide.

Fig. 5 Distance between two particles of different sizes during the movement under ideal assumption



2. The distance between m1 and m2 is suitable that the interaction force F_r will exist: The two particles are moving together along the direction of magnetic field, and finally they stick together to form agglomerates.

Fig. 6 Distance between two particles during the movement under static gradient magnetic field



3. With the setup of alternating gradient field, the two particles are mutually exclusive of each other periodically, preventing the aggregation. The curve is fluctuating due to the intermittent change of force. The frequency of altering gradient field is higher(the shift is faster), the separation efficiency is better.

Fig. 7 Distance between two particles during the movement under an oscillating gradient magnetic field

Conclusions

- ❖ Magnetic particles are observed to align and aggregate into multi-particle clusters in an applied magnetic field.
- ❖ Design of an alternating gradient magnetic field could be utilized to solve the aggregation problem between particles.
- ❖ To validate the feasibility of this method, the aggregation and separation behavior of magnetic particles with different sizes is numerically investigated, showing that the two types of particles could be separated effectively under the dynamic field.