Segregation Behavior of Super Paramagnetic Fe_3O_4 Nanoparticles in Solution Flowing in Gradient Magnetic Field

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Abstract. Oxygen and nitrogen molecules in liquid air may segregate in gradient magnetic field, which has potential applications in medicine, industry and other fields. According to the segregation behavior of magnetic nanoparticles in gradient magnetic field, magnetic drug carrier particles can be directionally guided to target areas in target therapy, which will improve the utilization of drugs and reduce the side effects of drugs on organs. We prepared super paramagnetic Fe_3O_4 nanoparticles coated with ammonium citrate with average diameter 13nm. We explored the effects of solution flow rate and magnetic field gradient on the segregation behaviors of super paramagnetic Fe_3O_4 nanoparticles in spiral flow channel. Results show that nanoparticle segregation is obvious with low solution flow rate and high gradient magnetic field.

1. Introduction

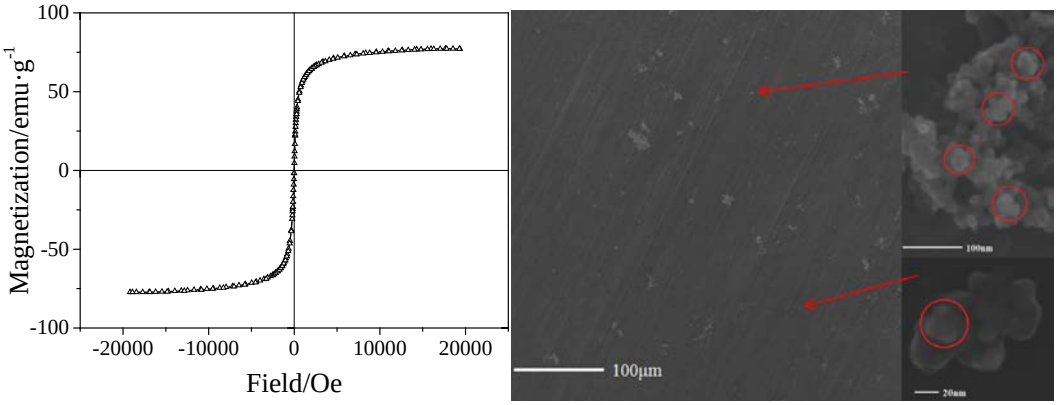
Oxygen and nitrogen molecules in liquid air can be considered as paramagnetic and diamagnetic particles. We proposed a method to enrich oxygen from liquid air based on oxygen molecules segregation in gradient magnetic fields. In addition, magnetic nanoparticles will segregate in gradient magnetic field, which is widely used in target therapy. In 1970s, K.J. Widder etc.[1] proposed the method of targeted therapy that magnetic drug carrier particles could be directed to the cancer organs in the effect of magnetic field. This method could concentrate the drugs in target organs and weak the side effects on other organs. C. Alexiou etc.[2] placed the permanent magnet on the rabbit skin surface under which lesion existed in order to improve the concentration of drugs. A few drugs were concentrated in the diseased organ. Chen etc.[3,4] implanted single or multiple magnetic metal wires into the target areas and simulated the magnetic particles with diameter 0.2-10μm enriched in target areas under the external magnetic field. The motion direction of the magnetic particles could be changed in the gradient magnetic field. However, most researches on target therapy using the magnetic field are theoretical. The segregation behavior of magnetic nanoparticles was studied rarely in experiment. We designed the experimental apparatus to investigate the segregation behavior of super paramagnetic Fe_3O_4 nanoparticles influenced by solution flow rate and magnetic field gradient.

2. Material and method

2.1 Super paramagnetic Fe_3O_4 nanoparticles.

Super paramagnetic Fe_3O_4 nanoparticles coated with ammonium citrate with average diameter 13nm were synthesized by the co-precipitation method. Fig.1a is the hysteresis loop diagram of Fe_3O_4 nanoparticles at room temperature. This diagram shows the saturation magnetization of Fe_3O_4 nanoparticles is 77.267emu/g. The coercive force and the residual magnetization intensity are approximately zero, indicating that Fe_3O_4 nanoparticles show super paramagnetic properties. Fig.1b is scanning electron microscope (SEM) image of Fe_3O_4 nanoparticles. When the solution is naturally

dried, the nanoparticles became aggregates with various size. The aggregates consisted of many small aggregates as the red circles. The average diameter of small aggregates is 33nm.



(a) (b)

Fig.1 Hysteresis loop diagram and SEM image of Fe_3O_4 nanoparticles

2.2 Experimental apparatus.

When super paramagnetic Fe_3O_4 nanoparticles moves, segregation behavior of nanoparticles will be influenced by solution flow rate and magnetic field gradient. In order to explore the influences of these factors on the segregation behavior, we designed the flow channel as shown in Fig.2. The effective region is 0.5×76cm. The magnetic field gradient existing in the dashed box is perpendicular to the flow direction of solution. We insert a splitter between outset a and outset b to avoid diffusion of nanoparticles when the nanoparticles leave the gradient magnetic field.

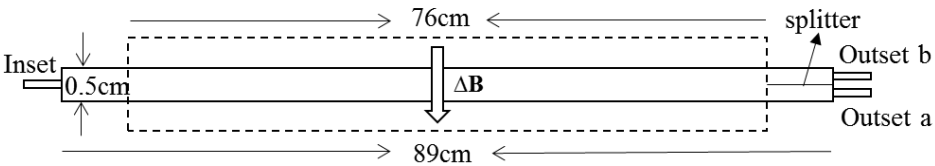


Fig.2 The flow channel apparatus

The distribution of magnetic field between the two iron cores of electromagnet is symmetrical, and the magnetic field changes by adjusting the current. When the current of electromagnet is 0.3A, the magnetic field distribution on the line L_1 is shown in Fig.3. The magnetic field gradients in both area I and II are 3T/m, while the directions are opposite. We spiral the flow channel into a virtical channel as Fig.3 and place the virtical channel in area I. The radius of the vertical channel is 4.4cm and the pitch is 0.7cm. Therefore, we obtain a gradient magnetic field in the axial direction of electromagnet to control the segregation behavior of nanoparticles and change the distribution of solution concentration. We used WDS-3 type grating spectrometer to measure solution concentration.

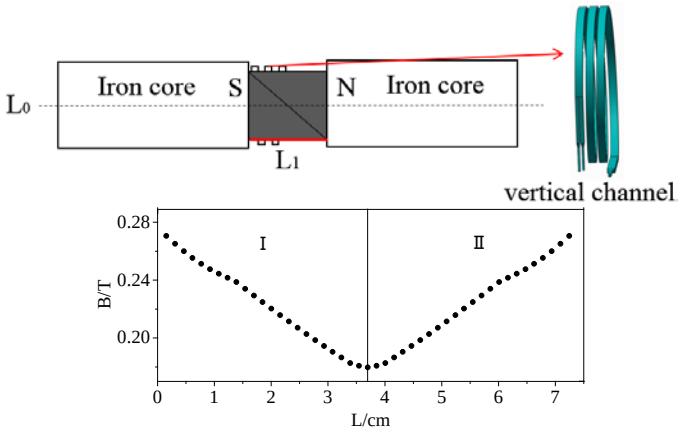
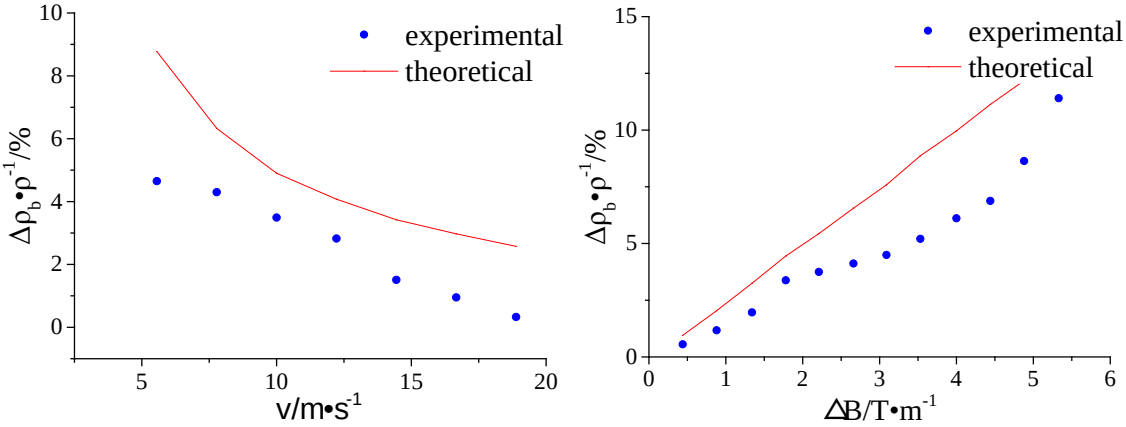


Fig.3 Experiment apparatus and magnetic field intensity on the line L_1 (the distance between the axis L_0 of electromagnet and line L_1 is 4.4cm)

3. Result

Solution flow rate would affect the segregation distance of super paramagnetic Fe_3O_4 nanoparticles in the gradient magnetic field. The solution with initial concentration 91.4mg/L flowed into the spiral flow channel in the 2.21T/m gradient magnetic field when the flow rate was 5.6cm/s, 7.8cm/s, 10.0cm/s, 12.2cm/s, 14.4cm/s, 16.7cm/s and 18.9cm/s, respectively. As Fig.4a, the concentration changes between the solution of outset b and the initial solution gradually decreased with the increase of solution flow rate.



(a) (b)

Fig.4 Effects of solution flow rate and magnetic field gradient on the concentration changes between the solution of outset b and the initial solution

The segregation distance of the nanoparticles could be changed by the magnetic field force, which could be improved by increasing the magnetic field gradient. The solution with initial concentration 100.3mg/L flowed into the spiral flow channel at 10.0cm/s flow rate when the magnetic field gradient was 0.88T/m, 1.34T/m, 1.78T/m, 2.21T/m, 2.66T/m, 3.09T/m, 3.53T/m, 4.00T/m, 4.44T/m and 5.33T/m, respectively. As Fig.4b, the concentration changes between the solution of outset b and the initial solution are gradually enhanced with the increase of the magnetic field gradient. Especially, the changes increase rapidly when the magnetic field gradient exceeds 4.44T/m.

4. Discussion

The distribution of super paramagnetic Fe_3O_4 nanoparticles in solution is influenced by the magnetic force and the stokes force when the solution flows into the spiral flow channel. The magnetic force promotes the segregation of the super paramagnetic Fe_3O_4 nanoparticles. On the contrary, the stokes force hinders the segregation.

When the nanoparticles leave the gradient magnetic field, the segregation distance of the nanoparticles is:

$$\mathbf{S} = \mathbf{S}_{\mathrm{P}} + \mathbf{S}_{\perp} \tag{1}$$

$$S_{\mathrm{P}} = X\ ,\ S_{\perp} = \int_0^{\frac{X}{v_f}} \frac{\rho_p V_p M\left(B(x)\right)}{3\pi\eta_f d_p} \cdot \Delta B d\left(\frac{x}{v_f}\right)$$

S_{P}: effective length of the spiral flow channel, $S_{\perp}$: segregation distance of particle in perpendicular to solution flow rate

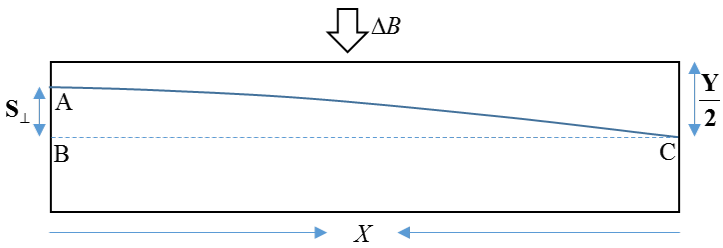


Fig.5 Segregation diagram of super paramagnetic Fe_3O_4 nanoparticles in the gradient magnetic field

If the nanoparticle at point A could exactly arrive at point C where the splitter located, nanoparticles between point A and B could segregate to outset a. Thus, the concentration changes between the solution of outset b and the initial solution could be described as:

$$\frac{\Delta\rho_b}{\rho} = \frac{\rho - \rho_b}{\rho} = \frac{2S_\perp}{Y} \tag{2}$$

Therefore, the concentration changes between the solution of outset b and the initial solution could be obtained theoretically by the segregation distance of nanoparticle in solution.

Fig.4a is the experimental results and the theoretical results of the changes at different flow rates, and Fig.4b is the changes at different magnetic field gradients. The trend of the theoretical results is basically consistent with the experimental results. Super paramagnetic Fe_3O_4 nanoparticles are magnetized in the gradient magnetic field to generate an additional gradient magnetic field, which enriching the nanoparticles around them. The additional gradient magnetic field in the surface of the nanoparticles is much larger than that where is far away the nanoparticles. When the additional magnetic field gradient induced by the nanoparticles exceeds a certain value, the agglomeration of nanoparticles may be enhanced. The concentration changes and the segregation distances will increase.

5. Summary

The segregation of super paramagnetic Fe_3O_4 nanoparticles in solutions flowing into a gradient magnetic field is affected by solution flow rate and magnetic field gradient. Segregation of nanoparticles is obvious with low solution flow rate and high gradient magnetic field. Enhancing the magnetic field gradient, the agglomeration of nanoparticles increases,and the segregaion enhances.

Acknowledgements

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