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Study of coercive force for $y\text{ZnFe}_2\text{O}_4$–$(1-y)\text{CoFe}_2\text{O}_4$ magnetic nanoparticles system

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The coercive forces are taken out from the loops of magnetisation cycle for $y\text{ZnFe}_2\text{O}_4$–$(1-y)\text{CoFe}_2\text{O}_4$ mixed magnetic nanoparticles system (y is the volume fraction of ZnFe_2O_4 particles in $y\text{ZnFe}_2\text{O}_4$–$(1-y)\text{CoFe}_2\text{O}_4$ magnetic nanoparticles mixed system). The results show that the coercive force of the system is increasing with the y decreasing and is interpreted by using particles chain model. The number of chains of particles under magnetic field is obtained by comparing the coercive force of the experiment and the theory of chain model. In $y\text{ZnFe}_2\text{O}_4$–$(1-y)\text{CoFe}_2\text{O}_4$ magnetic nanoparticles mixed system, the coercive force comes from ferrimagnetic CoFe_2O_4 nanoparticles, and paramagnetic ZnFe_2O_4 nanoparticles make the chain length of the mixed magnetic system shorter than single CoFe_2O_4 nanoparticles system.

Keywords: magnetic nanoparticles; coercive force; interaction; chain

1. Introduction

The magnetic behaviour of magnetic orderly particles depends strongly on the particles' size. Small size effect of particles has influence not only on the macro-magnetic behaviour (such as saturation magnetisation), but also on the micro-interaction (reflected in the differences in magnetisation process). Ferrite nanoparticles MFe_2O_4 ($M=\text{Co}$, Mn and Zn etc. two divalent metal ion) are relatively stable; they are the most important part of preparing ferrofluids, which can be regarded as extensions or branches of the ultrafine particles of the research field. The in-depth study on magnetic nanoparticles will promote the development of ferrofluids. The ferrite particles whose size is around 10 nm are single domain particles, which can be regarded as a single magnetic moment. Under an external magnetic field, the magnetic moment of magnetic nanoparticles will tend to the external magnetic field direction, and with the strengthening of the external magnetic field, magnetisation gradually tends to saturation. This magnetisation process is closely related to the dipoles' interaction of inter-particles. In disperse systems (such as ferrofluids), the interaction of magnetic nanoparticles that affects magnetisation has been studied in both theory and experiment by many researchers and many models have been put forward, but

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a unified understanding of their mechanism has not yet been achieved [1–6]. There is distribution of particles size in the real ferrofluids, and it is a polydispersed system [7]. The properties of ferrofluids (magnetic property, microstructurer, viscosity and so on) are different from those of a monodispersed system, and there are many difficulties in discussing the mechanism on the properties. In recent years, there have been a few theoretical researches into bidispersed systems consisting of large and small size particles without size distribution [7–10], but such a system is hard to achieve in experiment. The magnetic moment **m** of single domain particles is proportional to volume V and the magnetic moment **m** of spherical particles can be expressed as:

$$m = \frac{\pi d^3 M}{6} \tag{1}$$

where M is the particles' magnetisation and d is the particles' size.

Therefore, the bi-system consisting of both large and small particles can also be regarded as a system consisting of stronger and weaker magnetic particles with different m from different d. Through the way that synthesising the system consisted of two different magnetic particles to study the bidispersed system, in other words, using the magnetic bidispersed system instead of the size bidispersed system, it is easier to discuss the property of nanoparticles system accurately by combining both experiments and theories.

Bulk $CoFe_2O_4$ is ferromagnetic, while bulk $ZnFe_2O_4$ is anti-ferromagnetic. Fine particles of anti-ferromagnetic bulk materials may be paramagnetic [11]. A mixture of two different magnetic nanoparticles is a kind of solid dispersed system, which is helpful to study the effect that interaction of particles has upon magnetic. In this article, the coercive force of $y\mathrm{ZnFe_2O_4}$–$(1-y)\mathrm{CoFe_2O_4}$ magnetic nanoparticles system ($y = 0, 1, 0.33, 0.5, 0.67, 0.8$) is measured and the role of weak magnetic particles in a system of magnetical bidispersion is studied.

2. Experimental methods

2.1. *The preparation of the nanoparticles*

With $FeCl_3 \cdot 6H_2O$, $ZnCl_2$, $Co(NO_3)_2 \cdot 6H_2O$, NaOH, HCl as raw materials, nanoparticles were prepared by chemical co-precipitation.

The following procedure was used:

(a) A proper proportion of NaOH solution was added to mixed solutions of $ZnCl_2$ and $FeCl_3$ by molar ratio 1 : 2 and the solutions were then heated until boiling. The solutions were boiled for 10 min and maintained at room temperature for 2 h. Then by washing, acetone dehydration and drying process, $ZnFe_2O_4$ powders were produced.

(b) A proper proportion of NaOH solution was added to mixed solutions of $Co(NO_3)_2$ and $FeCl_3$ by molar ratio 1 : 2 and the solutions were then heated to boiling. The solutions were boiled for 3 min and maintained at room temperature for 2 h. Then by washing, acetone dehydration and drying process, $CoFe_2O_4$ powders were produced.

(c) $0.5\mathrm{ZnFe_2O_4}$–$0.5\mathrm{CoFe_2O_4}$ ($y = 0.5$) nanoparticles system was produced by fully mixing $ZnFe_2O_4$ powders and $CoFe_2O_4$ powders at volume ratio 1 : 1.

$0.8ZnFe_2O_4$–$0.2CoFe_2O_4$ ($y = 0.8$) nanoparticles system was produced by fully mixing $ZnFe_2O_4$ powders and $CoFe_2O_4$ powders at volume ratio 4 : 1. Similarly, we can obtain $0.33ZnFe_2O_4$–$0.67CoFe_2O_4$ ($y = 0.33$) nanoparticles system and $0.67ZnFe_2O_4$–$0.33CoFe_2O_4$ ($y = 0.67$) nanoparticles system.

(d) X-ray diffraction (XRD, D/Max-RC) was used to analyse structures of the above samples, energy dispersive spectrometer of X-ray (EDX, Norton 8000) was used to analyse the atom ratio between M (Co, Zn) and Fe, and transmission electron microscopy (TEM,H-600) was used to observe the particle morphology and analyse/examine the particle size.

2.2. *The measurement of the magnetic properties*

HH-15 vibrating sample magnetometer (VSM) was used to measure the specific magnetisation σ curves of the six samples at room temperature and the largest magnetic field was 0.95 T. The specific saturation magnetisation of the $CoFe_2O_4$ nanoparticles is estimated from the relation of $\sigma_s \sim 1/H$ in high field [12]. The magnetisation M is achieved by

$$M = \sigma \cdot \rho \tag{2}$$

where ρ is the density of the nanoparticles. To the $yZnFe_2O_4$–$(1-y)CoFe_2O_4$ particles system, the density is

$$\rho = y \times \rho_1 + (1-y) \times \rho_2 \tag{3}$$

where ρ_1 is the density of $ZnFe_2O_4$, ρ_2 is the density of $CoFe_2O_4$, $\rho_1 = 5.32\,\mathrm{g\,cm^{-3}}$ and $\rho_2 = 5.23\,\mathrm{g\,cm^{-3}}$, respectively.

3. Experimental results and analysis

3.1. *The XRD and EDX measurement of the particles*

The XRD spectra of $ZnFe_2O_4$ and $CoFe_2O_4$ particle samples are given in Figure 1. From Figure 1(a) and (b), it can be seen that the diffraction peak is broad while the particle size is very fine. By analysing XRD spectra of the two samples, it can be determined that the above two samples are $ZnFe_2O_4$ and $CoFe_2O_4$ particles, respectively.

The crystallite size, D_{311}, was obtained, determined by the Scherr formula using the half-maximum width of the (311) X-ray diffraction line (Figure 1(a) and (b)) : $D_{XRDZnFe2O4} = 4.05\,\mathrm{nm}$, $D_{XRDCoFe2O4} = 10.06\,\mathrm{nm}$.

The atom ratio of about 1 : 2 between M(Co, Zn) and Fe by EDX for both $CoFe_2O_4$ and $ZnFe_2O_4$ particles can be obtained. The quantitative results for the samples are listed in Table 1.

3.2. *The morphology and size of the particles from TEM*

TEM observation indicated that the morphologies of both the $CoFe_2O_4$ and $ZnFe_2O_4$ particles are basically spherical as shown in Figure 2.

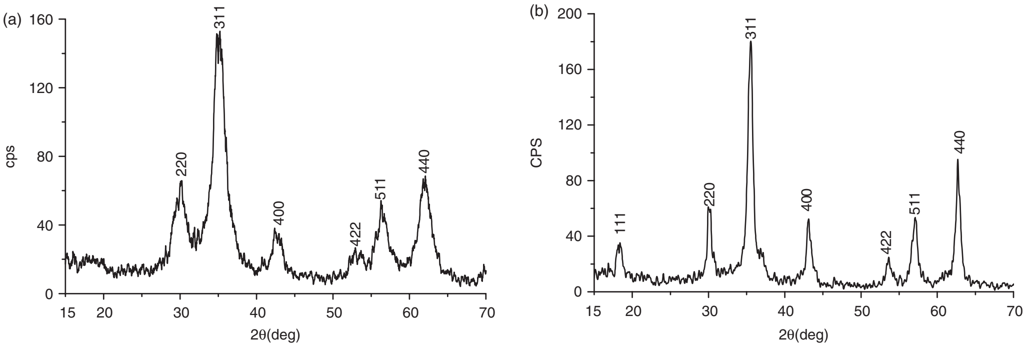


Figure 1. (a) XRD spectra of $ZnFe_2O_4$ particles and (b) XRD spectra of $CoFe_2O_4$ particles.

Table 1. The quantitative results of EDX.

Element	Atom%	Atom% error	Element	Atom%	Atom% error
Fe	67.20	+/− 1.19	Fe	63.10	+/− 1.14
Co	32.80	+/− 1.30	Zn	36.90	+/− 2.03
Total	100		Total	100	

Using statistical analysis from TEM photographs, the size distribution of $CoFe_2O_4$ can be illustrated as particles shown in Figure 3(a). The median value of the particles' diameter is 12.76 nm and the distribution function is as follows:

$$f(x)_{\mathrm{CoFe_2O_4}} = \frac{1.1366}{x}\exp\left[-4.06(\ln x - 2.55)^2\right]. \tag{4}$$

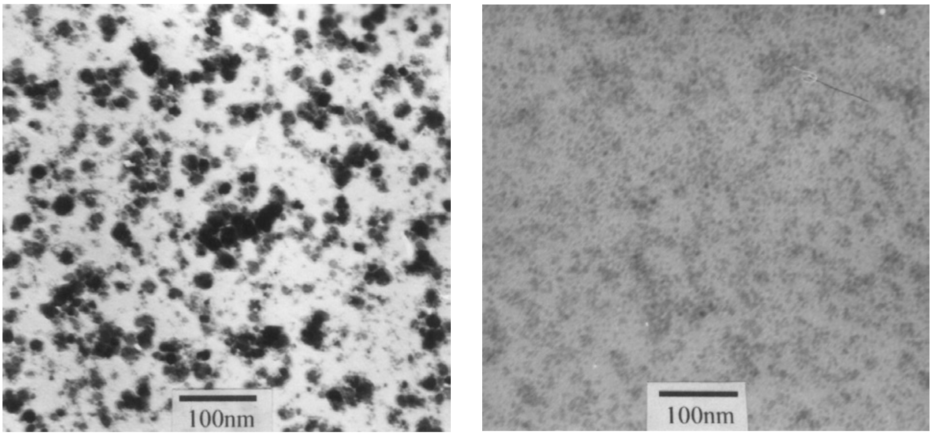
The size distribution of $ZnFe_2O_4$ particles can be also illustrated as shown in Figure 3(b). The median value of the particles' diameter is 4.22 nm and the distribution function is as follows:

$$f(x)_{\mathrm{ZnFe_2O_4}} = \frac{1.5341}{x}\exp\left[-7.39(\ln x - 1.44)^2\right]. \tag{5}$$

The sizes from the TEM photographs measurements are larger than the X-ray measurements.

3.3. *Measurement of magnetisation curves*

Measurement results of the curves of magnetisation cycle for the six samples are shown in Figure 4. The coercive force H_c is obtained from the magnetisation loops of the particles at room temperature, as shown in Table 2. Obviously, H_c decreases as y increases.



(a) (b)

Figure 2. TEM photographs of (a) $CoFe_2O_4$ particle and (b) $ZnFe_2O_4$ particle.

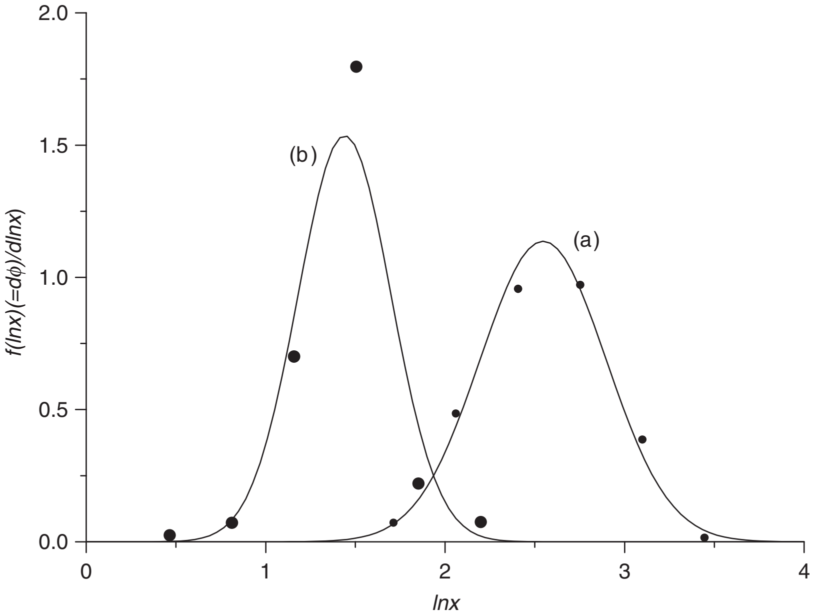


Figure 3. The size distribution for the (a) $CoFe_2O_4$ particles and (b) $ZnFe_2O_4$ particles. ● experiment values of $ZnFe_2O_4$ particles; • experiment values of $CoFe_2O_4$ particles; (—) curves of distribution.

The saturation magnetisation M_s of $CoFe_2O_4$ particles obtained by $M \sim 1/H$ relations at the high fields is $10^3\,A \cdot M^2$. $ZnFe_2O_4$ particles are paramagnetic and M value is $10^3\,A \cdot M^2$ at 0.95 T.

The critical diameter of the single-domain magnetic for cubic crystal system [13]:

$$D_c = \frac{9\sqrt{AK}}{\pi M_s^2}. \tag{6}$$

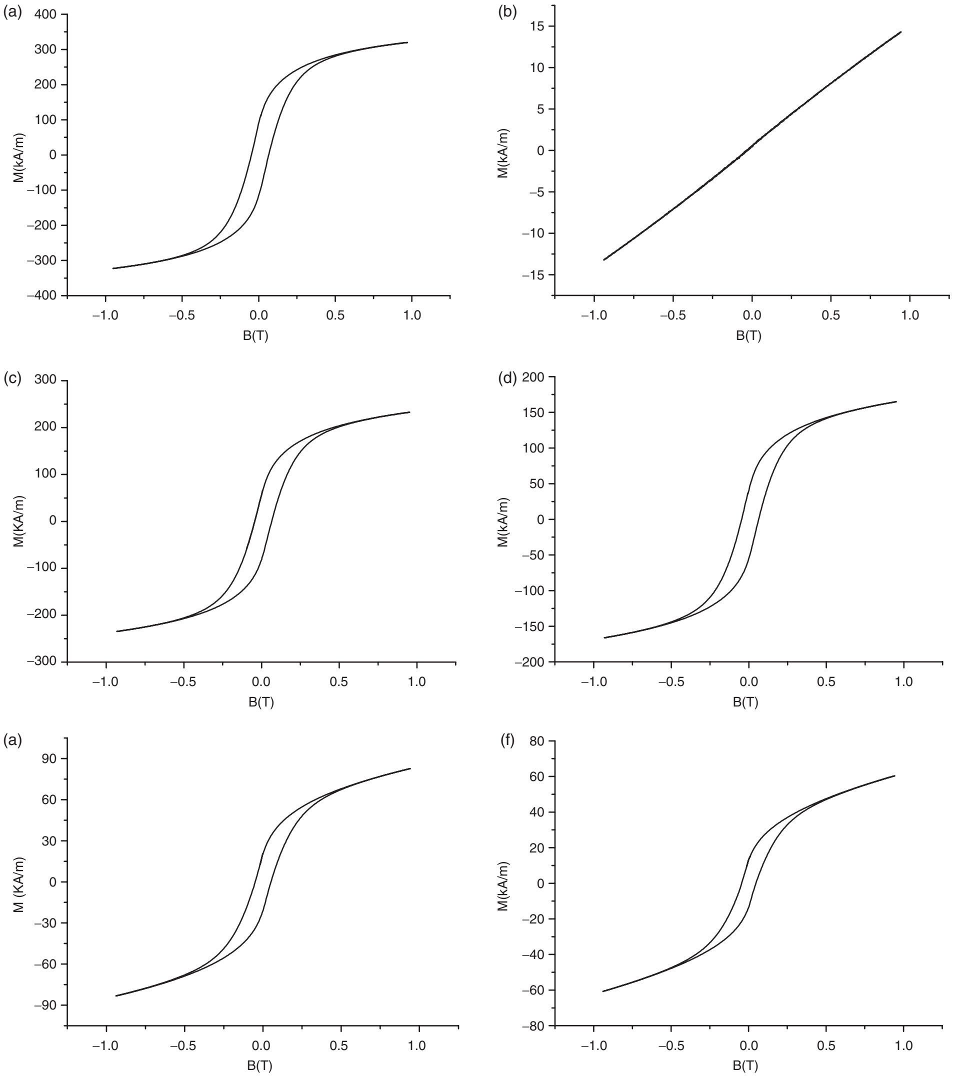


Figure 4. The magnetisation loops of $y\mathrm{ZnFe_2O_4}$–$(1-y)\mathrm{CoFe_2O_4}$ mixed magnetic nanoparticles system, (a) $CoFe_2O_4$ particles, (b) $ZnFe_2O_4$ particles, (c) $0.33ZnFe_2O_4$–$0.67CoFe_2O_4$ particles, (d) $0.5ZnFe_2O_4$–$0.5CoFe_2O_4$ particles, (e) $0.67ZnFe_2O_4$–$0.33CoFe_2O_4$ particles and (f) $0.8ZnFe_2O_4$–$0.2CoFe_2O_4$ particles.

Table 2. The coercive force H_c measured by VSM for $y\mathrm{ZnFe_2O_4}$–$(1-y)\mathrm{CoFe_2O_4}$ nanoparticles system mixed.

y	0	0.33	0.50	0.67	0.80	1
H_c ($\mathrm{kA\,m^{-1}}$)	44.47	43.70	43.65	39.37	36.37	0

where K is the anisotropy constant, M_s is the saturation magnetisation, A is the exchange constant and can be estimated from $A \approx k_B T_c/a$, where k_B is the Boltzmann constant, T_c is the Curie temperature, a is the crystal lattice constant.

When the values of bulk $CoFe_2O_4$ are substituted into Equation (6) ($K = 1.8 \times 10^6\,\mathrm{erg\,cm^{-3}}$, $M_s = 400\,\mathrm{Gs}$, $T_c = 793\,\mathrm{K}$, $a = 0.838\,\mathrm{nm}$), we can obtain $D_c = 274.513\,\mathrm{nm}$.

At room temperature, the superparamagnetic critical size of $CoFe_2O_4$ particles is about 14 nm [14]. The range of the size is 4.6–36.8 nm for $CoFe_2O_4$ particles diameter measured. Therefore, the $CoFe_2O_4$ particles consist of ferromagnetic and superparamagnetic particles. The ratio of superparamagnetic particles in $CoFe_2O_4$ particles number can be obtained as

$$\int_0^{14} f(x)_{\mathrm{CoFe_2O_4}}\mathrm{d}x = \int_0^{14} \frac{1.1366}{x}\exp[-4.06(\ln x - 2.55)^2]\mathrm{d}x = 0.6.$$

This shows that the $CoFe_2O_4$ particles prepared are single domain ones. The superparamagnetic particles number is 60% and the ferromagnetic particles number is 40% at room temperature.

4. Discussion

4.1. *Interaction energy the particles*

According to the diameter distribution function of $CoFe_2O_4$ nanoparticles (4), the average magnetic moment is [15]

$$\begin{aligned}\langle m\rangle &= \frac{\pi}{6}M_s\int_0^{\infty} x^3 f(x)\mathrm{d}x\\ &= 6.89 \times 10^{-19}(\mathrm{A\,m^2}).\end{aligned}$$

$ZnFe_2O_4$ particles are paramagnetic and the greatest average magnetic moment in the magnetic field is

$$\langle m\rangle = \frac{\pi}{6}M_{0.95\mathrm{T}}\int_0^{\infty} x^3 f(x)\mathrm{d}x$$

where $M_{0.95\mathrm{T}}$ is the magnetisation at 0.95 T. Substituting $M_{0.95\mathrm{T}}$ and $ZnFe_2O_4$ diameter distribution function (5), thus

$$\langle m\rangle = 7.61 \times 10^{-22}(\mathrm{A\,m^2}),$$

obviously, the average magnetic moment between $CoFe_2O_4$ particles is far bigger than the biggest magnetic moment of $ZnFe_2O_4$ particles.

The interaction of single-domain magnetic particles can be regarded as the interaction of magnetic dipole. Interaction energy between i and j magnetic dipole is expressed [16] by:

$$w = \left(\mu_0 m_i m_j/4\pi r_{ij}^3\right)\left[\cos(\theta_i - \theta_j) - 3\cos\theta_i\cos\theta_j\right] \tag{7}$$

where μ_0 is the vacuum permeability, r_{ij} is the particles' distance, θ_i, θ_j are the angle between magnetic moment and central connections line. When $\theta_i = \theta_j = 0$, the interaction energy of two $CoFe_2O_4$ dipole particles (diameter 12.76 nm) linked by head-to-tail ($r_{ij} = a$), can be calculated as about 2.63×10^{-20} J. When the magnetic moment of $ZnFe_2O_4$ is the largest of all, the interaction energy of two $ZnFe_2O_4$ dipole particles (diameter 4.22 nm) is about 1.14×10^{-24} J. While one $CoFe_2O_4$ particle with $m = 6.89 \times 10^{-19}(\mathrm{A\,m^2})$ and one $ZnFe_2O_4$ particle with $m = 7.61 \times 10^{-22}(\mathrm{A\,m^2})$ are linked by head-and-tail (r_{ij} = (diameter of $CoFe_2O_4$ particles + diameter of $ZnFe_2O_4$ particles)/2), the interaction energy is about 1.04×10^{-22} J. At room temperature, the thermal energy is about $k_BT = 4.14 \times 10^{-21}$ J. Therefore, it can be known that only the dipole interaction of $CoFe_2O_4$ particles would be larger than the thermal energy, so that the chain of $CoFe_2O_4$ particles will form in the magnetisation process [17]. So, a system mixed with both $CoFe_2O_4$ and $ZnFe_2O_4$ particles can be called a system of magnetical bidispersion.

4.2. *The coercive force*

If there is no interaction between particles, the magnetisation M of the mixture containing N types of particles can be expressed [18] by

$$M(B) = \frac{\sum_{n=1}^{N} M_n(B)\Phi_{Vn}}{\sum_{n=1}^{N} \Phi_{Vn}} \tag{8}$$

where M_n is the magnetisation, and Φ_{Vn} is the volume fraction of the n particle. Here, Φ_{Vn} has the same meaning as y and $(1-y)$ for yZnFe$_2$O$_4$–$(1-y)$CoFe$_2$O$_4$ nanoparticles system.

Thus, the remanence of yZnFe$_2$O$_4$–$(1-y)$CoFe$_2$O$_4$ nanoparticles system mixed is

$$M'_r(y) = (1-y)M_{r,Co} \tag{9}$$

where $M_{r,Co}$ is the remanence of the $CoFe_2O_4$ nanoparticles (i.e. $y = 0$ in yZnFe$_2$O$_4$–$(1-y)$CoFe$_2$O$_4$ system). So, the remanence for $M'_r$of yZnFe$_2$O$_4$–$(1-y)$CoFe$_2$O$_4$ nanoparticles system mixed can be calculated by Equation (9), as shown in Table 3. For comparison, the experiment values are also shown in Table 3.

Obviously, with y increasing, and the $CoFe_2O_4$ particle volume fraction deceasing, the experiment value M_r is much less than the calculation value M'_r of the remanence. But, it should be noticed that the coercive force decreases as y increases (Table 2). So, it can be judged that there is interaction in yZnFe$_2$O$_4$–$(1-y)$CoFe$_2$O$_4$ nanoparticles mixed system. The coercive force can be related to the aggregate of the $CoFe_2O_4$ nanoparticles, and $ZnFe_2O_4$ nanoparticles can prevent $CoFe_2O_4$ nanoparticles from aggregating in the nanoparticles mixed system [19]. Therefore, the coercive force can be discussed from the chain aggregate model.

Table 3. The calculation and experiment value of the remanence for yZnFe$_2$O$_4$–$(1-y)$CoFe$_2$O$_4$ nanoparticles system.

Y	0.00	0.33	0.50	0.67	0.80	1.00
M'_r (kA m^{-1})	256	68.74	51.30	33.06	20.52	0
M$_r$ (kA/m)	256	69.20	47.41	20.73	13.34	0
$\lvert M_r - M'_r \rvert \times 100/M'_r$ (%)	0	0.67	7.58	37.30	35.01	0

If there is no external magnetic field, the intrinsic magnetic moment of ferromagnetism or ferrimagnetism nanoparticles will be random in orientation. Under the magnetic field, the magnetic moment of the nanoparticles will have a tendency to link along the direction of the magnetic field. Because the interaction energy of $CoFe_2O_4$ particles linked by head-and-tail is larger than the thermal energy, $CoFe_2O_4$ particles form a chain-like aggregate structure. When the magnetic field increases towards the negative direction, the magnetic moment along the positive direction will reverse first until the magnetic moments are opposite to the negative direction; then the corresponding magnetic field is the coercive force of the system. The magnetic reversal of the chain of spheres may have two mechanisms. One is the magnetic moment parallel rotation mechanism; the other is the symmetric fanning mechanism [20], as shown in Figure 5. In the two models of Figure 5, the spheres are all isolated; no consideration of their magnetic anisotropy is taken and, if it is assumed the particles are idealistic contacts, there only exists the magnetic dipole interaction of particles.

In order to calculate the coercive force of spheres' chain under the magnetic field, first of all the total energy of the chain should be taken into account. Disregarding magnetic anisotropy energy, the total energy of the chain is only composed of interaction energy of both the interdipoles and between the dipoles and magnetic field. The total energy is the function of angle between magnetic moment and external magnetic field. Coercive force can be obtained from the energy relationship [20]. In order to simplify the discussion, assume the magnetic moment as the average magnetic moment. Let the number of particles in a chain be *n*. The total energy can be expressed in parallel rotating mechanism as:

$$w_n = (\mu_0 m^2/4\pi a^3) n K_n (1 - 3\cos^2\theta) + n\mu_0 m H \cos\theta \tag{10}$$

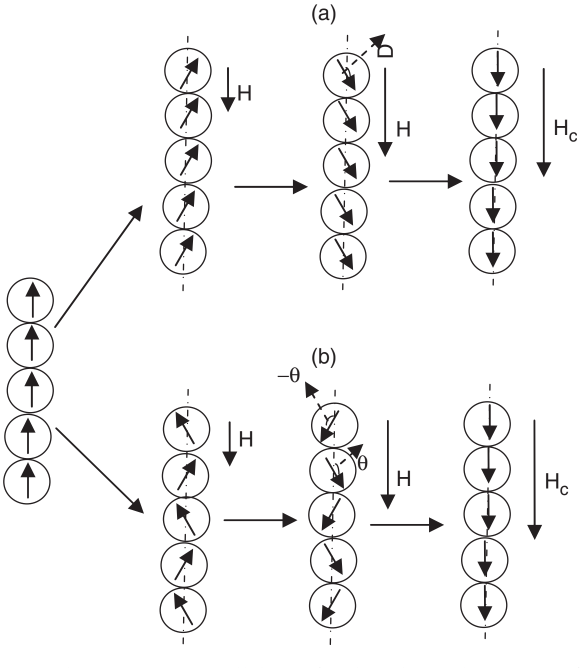


Figure 5. Rotating magnetic moment parallel mechanism inversion (a) and symmetric magnetic moment of the fan inversion mechanism (b).

where

$$K_n = \frac{\sum_{j=1}^{n}(n-j)}{nj^3}.$$

In the magnetisation process, the magnetic moment will rotate as the magnetic field increases. The conditions of the balance are

$$\frac{\partial w_n}{\partial \theta} = 0.$$

From Equation (10) we can obtain

$$\frac{\partial w_n}{\partial \theta} = (\mu_0 m^2/4\pi a^3) n K_n (6\cos\theta\sin\theta) - n\mu_0 m H \sin\theta = 0.$$

Thus,

$$H = (m/4\pi a^3) 6 K_n \cos\theta. \tag{11}$$

When the magnetic moment of the chain of spheres is in complete reversal, $\theta = \pi$, the coercive force can be expressed

$$H_{\mathrm{c},n} = (m/4\pi a^3) 6 K_n. \tag{12}$$

In the symmetric fanning mechanism, the total energy can be expressed as:

$$\begin{aligned} w_n = {} & (\mu_0 m^2/4\pi a^3) n L_n (\cos 2\theta - 3\cos^2\theta) + (\mu_0 m^2/4\pi a^3) n M_n (1 - 3\cos^2\theta) \\ & + n\mu_0 m H \cos\theta \end{aligned} \tag{13}$$

where

$$L_n = \sum_{j=1}^{\frac{1}{2}(n-1) j \le \frac{1}{2}(n+1)} [n-(2j-1)]/n(2j-1)^3$$

$$M_n = \sum_{j=1}^{\frac{1}{2}(n-2) j \le \frac{1}{2}n} (n-2j)/n(2j)^3 \quad L_n + M_n = K_n.$$

Using the same method with the parallel rotating mechanism, we can obtain the coercive force of symmetric fanning reversal mechanism as

$$H_{\mathrm{c},n} = (m/4\pi a^3)(6K_n - 4L_n). \tag{14}$$

For single $CoFe_2O_4$ particles, according to Equations (12) and (14), the relationship between particles number in a chain n and coercity H_c can be calculated for two mechanisms respectively. The partial results calculated are listed in Table 4.

From Table 4, it can be seen that, as the particles number in the chain increases, the coercive force becomes higher and higher. In the magnetic moment parallel reversal mechanism and the symmetry fanning reversal mechanism, the coercive force of the former is larger than the latter. The coercive force of $CoFe_2O_4$ can be obtained as $H_\mathrm{C} = 44.47\,\mathrm{kA\,m^{-1}}$ from the experiment. Comparing the theory result of the above two

Table 4. The relationship between the particles number in a chain n and coercive force H_c.

	H_c (kA m^{-1})	
n	A	B
1	0	0
2	45.51	15.17
7	88.94	35.51
8	91.40	36.70
9	93.33	37.64
10	94.89	38.40
39	105.60	43.69
64	107.08	44.42
100	107.91	44.84
1000	109.26	45.51
10,000	109.39	45.58
100,000	109.40	45.58

A – parallel reversal mechanism of magnetic moment; B – symmetry fanning reversal mechanism of magnetic moment.

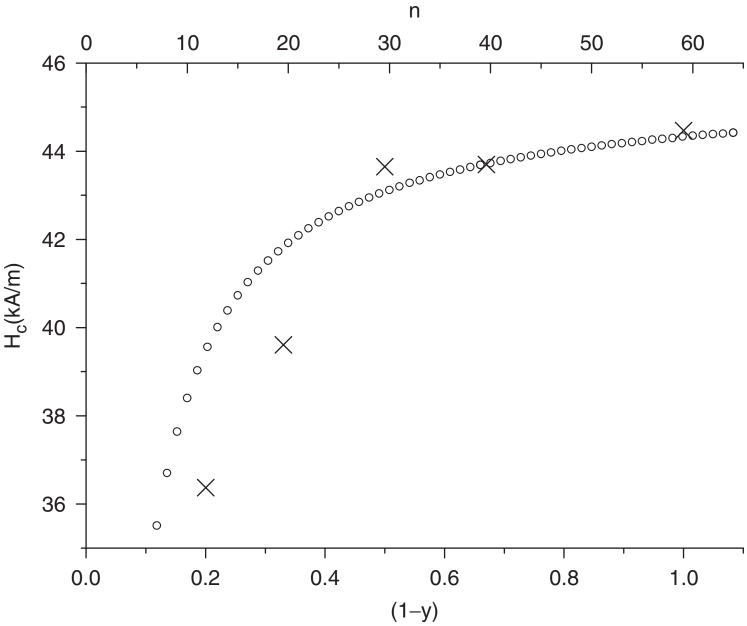


Figure 6. The relations of the coercive H_c versus the $CoFe_2O_4$ particle volume fraction $(1-y)$, and versus $CoFe_2O_4$ particles number in a chain n for the symmetry fanning reversal model of chain. × – H_c versus $(1-y)$, ○ – H_c versus n.

models, it can be known that the experimental result is consistent with the symmetry fanning reversal mechanism and that the corresponding number of particles is about 64.

In yZnFe$_2$O$_4$–$(1-y)$CoFe$_2$O$_4$ magnetic nanoparticles mixed system, $ZnFe_2O_4$ is weak magnetic particles and its coercive force is 0. Compared with the magnetic of

$CoFe_2O_4$, the magnetic of $ZnFe_2O_4$ can be neglected. For the bidispersed system constituted with strong and weak magnetic nanoparticles, strong magnetic $CoFe_2O_4$ particles may form a chain of spheres aggregating which present in a 'sea' of weak magnetic $ZnFe_2O_4$ particles [21]. Therefore, the coercive force of the $yZnFe_2O_4$–$(1-y)CoFe_2O_4$ magnetic nanoparticles system is still produced by chains of $CoFe_2O_4$. According to the magnetic moment symmetry fanning reversal mechanism and the experimental results in Table 2, we can see that when the coercive force of $0.33ZnFe_2O_4$–$0.67CoFe_2O_4$ in experiment is 43.70 kA m^{-1}, the corresponding number of particles in the chain is 39; that when the coercive force of $0.5ZnFe_2O_4$–$0.5CoFe_2O_4$ in experiment is 43.65 kA m^{-1}, the corresponding number of particles in the chain is 29; that when the coercive force of $0.67ZnFe_2O_4$–$0.33CoFe_2O_4$ in experiment is 39.37 kA m^{-1}, the corresponding number of particles in chain is 20, and that when the coercive force of $0.8ZnFe_2O_4$–$0.2CoFe_2O_4$ in experiment is 36.37 kA m^{-1}, the corresponding number of particles in chain is only 8.

In Figure 6, the relations of coercive force H_c versus n and versus $(1-y)$ are shown. Clearly, both relations are similar and n has a linear relation with $(1-y)$. This shows that the length of the $CoFe_2O_4$ particles chains becomes shorter because of $ZnFe_2O_4$ particles mixing in the $yZnFe_2O_4$–$(1-y)CoFe_2O_4$ particles system.

5. Conclusions

The size of $CoFe_2O_4$ nanoparticles prepared is about 12.76 nm, while the particles size of prepared $ZnFe_2O_4$ is about 4.22 nm and the particles size of $ZnFe_2O_4$ is only one-third of $CoFe_2O_4$.

$yZnFe_2O_4$–$(1-y)CoFe_2O_4$ nanoparticles mixed system is a typical system of magnetism bidispersed. In this system, the coercive force merely comes from strong magnetic $CoFe_2O_4$ particles. From the characteristics of both the coercive force H_c decreasing and the remanence M_r deviating from the calculation value with the particle volume fraction of $ZnFe_2O_4$ particles y increasing as well as the average interaction energy of between the $CoFe_2O_4$ particles stronger than k_BT, it can be judged that the coercive force is in relation to $CoFe_2O_4$ nanoparticles aggregating for the $yZnFe_2O_4$–$(1-y)CoFe_2O_4$ $(0 < y < 1)$ nanoparticles system. Under the magnetic field, the strong magnetic particles would form a chain-like structure. The number of particles in a chain can be obtained from the coercive force. Comparing the $CoFe_2O_4$ nanoparticles with $yZnFe_2O_4$–$(1-y)CoFe_2O_4$ nanoparticles mixed system, we can know that weak magnetic particles make the chain length of particles shorter. This accords with the light transmission change law of ferrofluids made up of similar systems, which will be reported in another paper. Therefore, we can infer that speciality of ferrofluids of magnetism bidispersion may be different from one of magnetism monodispersion. This will be further researched.

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