An Experimental Validation Study of Ferrofluid Evaporation

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Abstract

Kerosene based ferrofluid was put into a test tube to evaporate under different conditions. The weight losses of samples were measured and the evaporation rates were calculated. The predictions of evaporation rates were made based on Bolotov's model. It was found that the magnetic particles prevent the base fluid from evaporation and lower volume fraction led to higher evaporation rate. Bolotov's model had a certain deviation but still well responsive to different variables. It was also found that the magnetic field made a difference to the evaporation rate.

Introduction

Ferrofluid, also known as magnetic fluid, is a nano-scale functional material, usually prepared by co-precipitation method^[1]. It has both the magnetic properties of a solid and the fluidity of a liquid. When there is no external magnetic field, the magnetic liquid is a Newtonian fluid. When a magnetic field is applied, the magnetic liquid exhibits magnetism and exhibits a non-Newtonian fluid behavior^[2].

Ferrofluid is a colloidal suspension of single-domain magnetic particles, which is composed of three parts, namely the magnetic particles, the surfactant and the base carrier liquid^[3,4]. The magnetic particles are in a diameter size ranging from 8–10 nm, coated with surfactant to keep liquid from agglomerating, dispersed in a base liquid. In the presence of a magnetic field, the magnetic particles will be reorganized making the whole body of fluid strongly magnetized.

Since first synthesis of a ferrofluid was produced by Papell^[5] in 1965, it has been applied in numerous industry fields^[6]: dynamic sealing^[7], heat conductor, dampers^[8], and drug targeting^[9], etc. Among them, the magnetic fluid seal is a new type of sealing method, which is different from the traditional sealing method in the past. The magnetic fluid seal has the advantages of zero leakage, long life, and high reliability^[10]. In the practical application of the magnetic fluid sealing device, the magnetic fluid exists in the gap between the pole tooth and the rotating shaft, forming several "O"-shaped sealing rings, which achieves the sealing effect^[11,12]. However, under the action of a magnetic field and a temperature field, the magnetic fluid will evaporate, causing changes in the properties of the magnetic fluid, resulting in a seal failure. To satisfy high quality standard and harsh conditions in practical applications, like monocrystalline silicon furnace and optical device, it is necessary to have further research on evaporation of ferrofluid.

To date, some studies have been done from different aspects. Bottenberg et al.^[13] prepared a polyphenylene ether-based ferrofluid. Compared with hydrocarbon-based ferrofluids, this ferrofluid has a lower saturated vapor pressure, which can reach 10⁻⁷ torr at 20°C. It is especially suitable for Sealing under high vacuum environment. Kanno et al.^[14] prepared a PFPE based ferrofluid, which had a vapor pressure of 7.0×10⁻¹⁰ Pa at 293 K and a resistance to active gasses. A PFPE based ferrofluid was prepared and characterized by Black et al.^[15], which was found to have low volatility under high temperature. Li et al.^[16] calculated the evaporation rate of hydrocarbon based and fluorocarbon based

ferrofluid under four different vacuum levels. Cristaldo et al.^[17–19] numerically analyzed heating process of ferrofluid droplet under an alternating magnetic field with a thermal boundary layer model. Bolotov et al. derived equations of evaporation rate to estimate the life of a tribounit with ferrofluid in the ambience of a vacuum^[20] and a gas^[21]. Jaiswal et al.^[22] and Chattopadhyay et al.^[23] studied the evaporation kinetics of a magnetic salt solution pendent droplet under a horizontal magnetic field. Experimental observations revealed that the evaporation rate enhanced with a magnetic field and magneto-solutal advection was thought to be the domineering factor in augmented evaporation rate. Mudra Jadav et al.^[24] placed water-based magnetic droplets on a flat glass substrate and studied the influence of a magnetic field on the evaporation rate and contact angle. The results showed that in the dry droplets, the structure and distribution of the nanomagnetic particles are related to the direction and magnitude of the applied field. Saedi, M et al.^[25] used a two-phase flow model and volume control technology to numerically study the boiling flow of pure fluid and nanofluid in a spiral tube. Studies have shown that the diameter of the coil affects the heat transfer coefficient, and it is found that the viscosity and density of the nanofluid also have an effect on the heat transfer coefficient. Mohammadpourfard, M et al.^[26] simulated the nuclear pool boiling heat transfer of a ferrofluid on a horizontal plate. The effects of the negative and positive gradients of the magnetic field on the heat transfer rate and bubble shape are compared. Shyam Sudip et al.^[27] studied the evaporation kinetics of a fixed ferromagnetic droplet placed on a soft substrate under the action of a time-dependent magnetic field. The time-varying magnetic field can effectively control the evaporation time of the ferromagnetic droplets, and a critical frequency of the applied magnetic field strength is determined, which makes the droplets encounter the minimum lifetime. At the critical frequency, the advection time scale of magnetic nanoparticles is balanced by the magnetic disturbance time scale.

Previous studies mainly focus on the characterization of ultra-low vapor pressure ferrofluid in a vacuum and theoretical analysis of evaporation process. However, there are lacks of researches to verify the equations being proposed and compare the difference of ferrofluid evaporation with and without a magnetic field in an experimental way. This paper analyzes the evaporation rate of a kerosene based ferrofluid in normal pressure with and without a magnetic field through experimental and theoretical studies.

Theoretical Research

Bolotov *et al.*[10] had derived the evaporation rate equation of ferrofluid from the Fick's First Law in several conditions. For the condition which the ferrofluid is in a vessel enclosed in a shell with a hole in Fig. 1, the equation can be written as:

$$W = \frac{DS_h p_s \mu}{R_0 T h} (1 - \omega_s) \left(1 + \frac{DS_h}{\alpha h S (1 - \omega_s)} \sqrt{\frac{2\pi\mu}{R_0 T}} \right)^{-1} \quad (1)$$

where

W evaporation rate of the ferrofluid;

D diffusion coefficient of the vapor molecules;

S_h surface area of the hole;

p_s saturated vapor pressure of the base fluid;

μ molar mass of the base fluid;

R_0 universal gas constant;

T absolute temperature of the ferrofluid;

h thickness of the hole;

S surface area of the ferrofluid;

α evaporation coefficient of the ferrofluid;

ω_s volume fraction of the magnetic particles.

According (1), for the condition which the ferrofluid is in a vessel like a test tube in Fig. 2, $S = S_h$ and h becomes the height from the surface of ferrofluid to the mouth of test tube. The equation can be written as:

$$W = \frac{DS p_s \mu}{R_0 T h} (1 - \omega_s) \left(1 + \frac{D}{\alpha h (1 - \omega_s)} \sqrt{\frac{2 \pi \mu}{R_0 T}} \right)^{-1} \quad (2)$$

To predict the evaporation rate with (2), the coefficient α and D need to be determined. In certain cases, coefficient α can be less than 1, but for the majority of substances $\alpha \approx 1$ ^[9]. Coefficient D can be calculated in reverse from the evaporation rate of base fluid in certain temperature and atmospheric pressure. Following equation can be used to get the D in other conditions:

$$D = D_0 \frac{p_{A0}}{p_A} \left(\frac{T}{T_0} \right)^{3/2}. \quad (3)$$

where D_0 is the known diffusion coefficient in certain temperature T_0 and atmospheric pressure p_{A0} , and D is the unknown diffusion coefficient in temperature T and atmospheric pressure p_A .

Experimental Study

A. Experimental materials and Device

The materials used in the experiment were kerosene and kerosene-based magnetic fluids with different volume fractions.

The device used in the experiment is: Hefei Anke Environmental Testing Equipment Co., Ltd. GDJS-1000L high and low temperature alternating damp heat test box, the temperature range is $-70^{\circ}\text{C}\sim+150^{\circ}\text{C}$, and the temperature error is $\pm 0.5^{\circ}\text{C}$. The test tube used is a cylindrical flat-bottomed transparent borosilicate glass test tube with a total height of 76mm and an inner diameter of 10mm. The balance used is an ME55 balance produced by METTLER TOLEDO, with a division value of 0.01 mg.

B. Experimental method

To verify the evaporation rate of ferrofluid with (2), a kerosene based ferrofluid and its base fluid kerosene have been tested. A test tube, which is 76 mm in height and 10mm in inner diameter, is filled with the sample. In some cases, a magnet is put under the test tube to provide a magnetic field. The test tube is put into a high temperature test chamber for 12 hours, shown in Fig. 3. During the process of evaporation, the sample's weight is measured every 3 hours by a precision electronic balance with a resolution of 0.01 mg to get the weight loss data, shown in Fig. 4. The height h is controlled properly to make sure that the influence of magnetic field on the surface area S is as little as possible.

The volume fraction ω_s can be obtained from the density of sample, which is about 13%. To prepare the ferrofluid with different volume fraction, the ferrofluid is diluted with the base fluid and then applied with ultrasonic treatment for couple of hours. Both the saturated vapor pressure p_s and molar mass μ can be looked up in handbooks.

Results And Discussion

A. Temperature

To study the influence of temperature on the evaporation process, ferrofluid and kerosene are put into the chamber at 50°C , 70°C and 90°C with a height $h = 41\text{mm}$ and $\omega_s = 13\%$. Figure 5 presents the weight loss of samples, which reveals that the evaporation rate of ferrofluid is lower than its base fluid. However, it also shows that the curve of weight loss is nearly a straight line but not strictly and the curve's gradient (evaporation rate) is getting lower. According to (2), this phenomenon can be attributed to the increase of h and ω_s in the evaporation process. To make the calculating condition more consistent with the reality, only the data set of first three hours is selected to represent the evaporation rate of samples.

Before the calculation with (2) to predict the evaporation rate of ferrofluid, the diffusion coefficient D is calculated in reverse from the evaporation rate of kerosene at 70°C , which $D_0 = 1.9964 \times 10^{-6} \text{ m}^2/\text{s}$. The prediction of evaporation rate for ferrofluid at different temperatures is shown in Fig. 6, which reveals that the deviation of evaporation rate between the prediction and the deviation is decreasing while the temperature getting higher.

B. Volume fraction

The ferrofluid with different volume fraction is prepared to study the relationship between the evaporation rate and the volume fraction then evaporates with a height $h = 41$ mm at $70\text{ }^{\circ}\text{C}$. Dilute ferrofluid with kerosene in proportion of three parts of ferrofluid to one part of kerosene and one part of ferrofluid to one part of kerosene. Figure 7 presents the result of experiment which reveals that the evaporation rate of diluted ferrofluid is intermediate between the undiluted ferrofluid and the kerosene. The more dilute the ferrofluid, the faster it is to evaporate, which clearly proves that the magnetic particles prevent the base fluid from evaporation. Figure 8 shows that the prediction values based on (2) are overestimated, but still reflect the difference between different dilution rate.

C. Height

The height h as a variable is also investigated. Undiluted samples with different height $h = 41$ mm and $h = 46$ mm are tested at $70\text{ }^{\circ}\text{C}$. Figure 9 shows the result of experiment which reveals that the higher h slows down the evaporation process obviously. Since the height has changed in the case of $h = 46$ mm, the diffusion coefficient D need to be recalculated, which $D_0 = 1.8941 \times 10^{-6} \text{ m}^2/\text{s}$. The predictions are given in Fig. 10, which shows a same overestimated result as above.

D. Magnetic field

The most distinguishing feature of ferrofluid is the response of the magnetic particles, dispersed in a base liquid, to a magnetic field. Considering the evaporation process of base fluid weakened by the magnetic particles, it is necessary to explore the influence of magnetic field on the evaporation rate. An explorative experiment is designed to compare the cases between the ferrofluid with and without a magnetic field at the bottom of test tube. Undiluted samples are put into the chamber with a height $h = 41$ mm at $70\text{ }^{\circ}\text{C}$.

The result is shown in Fig. 11, which shows the ferrofluid with a magnetic field has the evaporation rate intermediate between the ferrofluid without a magnetic field and the kerosene. This phenomenon might be attributed to the decreasing of local concentration near the level of ferrofluid, which makes the ferrofluid with lower volume fraction evaporate.

Conclusion

This paper analyzes the evaporation rate of kerosene based ferrofluid with different variables from experiments and predicts the evaporation rate based on the Bolotov's model. Some conclusions are listed as follows:

1. Ferrofluid has lower evaporation rate comparing with base fluid. It is clear that the magnetic particles prevent the base fluid from evaporation and lower volume fraction leads to higher evaporation rate.

2. Although the result of Bolotov's model has a certain deviation, it is still well responsive to different variables.
3. Magnetic field promotes the process of evaporation, which might be attributed to the decreasing of local concentration near the level of ferrofluid.

Considering Bolotov's model merely bases on the loss of surface area S due to the magnetic particles covering the evaporation surface, it is reasonable to guess that there are other factors functioning, which needs further study..

Declarations

A. Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

B. Competing interests

The authors declare no competing financial interests.

C. Funding

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D. Authors' contributions

The author' contributions are as follows: Decai Li was in charge of the whole trial; Wenjuan Yu and Sifang Niu did laboratory analyses and wrote the manuscript.

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F. Consent for publication

Not applicable

G. Ethics approval and consent to participate

Not applicable

References

1. LI Decai.(2010). Theory and Application of Magnetic Liquid Seal Beijing: Science Press.
2. CHI Changqing.(2011). Physics basis and application of ferrofluid. Beijing: Beihang University Press.
3. Charles S W, Popplewell J. (1982). Properties and applications of magnetic liquids. Endeavour, 6(4), 153–161.
4. Raj K, Moskowitz B, CASCIARI R.(1995). Advances in ferrofluid technology. Journal of magnetism and magnetic materials, 149(1–2), 174–180.
5. P. S. Stephen,(1965) "Low viscosity magnetic fluid obtained by the colloidal suspension of magnetic particles," ed: U.S. Patent.
6. C. Scherer and A. M. Figueiredo Neto.(2005). Ferrofluids: properties and applications. Brazilian Journal of Physics, 35(3), 718–727.
7. Rosensweig RE.(1985). Ferrohydrodynamics. Cambridge University Press.
8. LI Decai(2003). Theory and application of magnetic fluid. Beijing: Science Press.
9. J.M. Gallo, P.K. Gupta, C.T. Hung, D.G. Perrier.(1989). Evaluation of drug delivery following the administration of magnetic albumin microspheres containing adriamycin to the rat. Journal of Pharmaceutical Sciences, 78(3), 190–194.
10. Zhang, Y., et al.(2019). Experimental validation and numerical simulation of static pressure in multi-stage ferrofluid seals. IEEE Transactions on Magnetics, 55(3), 1–8.
11. CHI Changqing, WANG Zhishan, ZHAO Pizhi.(1993). Ferrohydrodynamics. Beijing: Beihang University Press.
12. Zou Jibin et al(2000). Principle and design of magnetic fluid seal. Beijing: National Defense Industry Press.
13. Bottenberg W R, Chagnon M S.(1982). Low-vapor-pressure ferrofluids and method of making same. US4315827.
14. T. Kanno, Y. Kouda, Y. Takeishi, T. Minagawa, and Y. Yamamoto.(1997). Preparation of magnetic fluid having active-gas resistance and ultra-low vapor pressure for magnetic fluid vacuum seals. Tribology international, 30(9), 701–705.
15. T. Black, K. Raj, and S. Tsuda.(2002). Characterization of an ultra-low vapor pressure ferrofluid. Journal of magnetism and magnetic materials, 252(1–3), 39–42.
16. Z. Li and K. Raj.(2005). Effect of vacuum level on evaporation rate of magnetic fluids. Journal of magnetism and magnetic materials, 289, 43–46,.
17. C. F. Cristaldo, M. M. Vargas, and F. F. Fachini.(2015). Ferrofluid droplet vaporization under very large magnetic power: Effects of pressure and effective thermal conductivity of liquid. Proceedings of the Combustion Institute, 35(2), 1613–1620.
18. C. F. Cristaldo and F. F. Fachini.(2013). Analysis of ferrofluid droplet combustion under very large magnetic power. Combustion and flame, 160(8), 1458–1465,
19. C. Cristaldo and F. Fachini.(2013). Ferrofluid droplet heating and vaporization under very large magnetic power: A thermal boundary layer model. Physics of Fluids, 25(3), 037101.

20. A. Bolotov, V. Novikov, and O. Novikova.(2016). Service Life of Magnetic Liquid Vacuum Tribounits. Procedia Engineering,150, 468–474.
21. A. Bolotov, V. Novikov, and O. Novikova.(2017). Life of magnetic-fluid frictional components in gas. Russian Engineering Research, 37(1), 27–31.
22. V. Jaiswal, R. K. Dwivedi, A. Harikrishnan, and P. Dhar.(2018). Magnetohydrodynamics-and magnetosolutal-transport-mediated evaporation dynamics in paramagnetic pendant droplets under field stimulus. Physical Review E, 98(1), 013109.
23. A. Chattopadhyay, R. K. Dwivedi, A. Harikrishnan, and P. Dhar.(2020). Ferro-advection aided evaporation kinetics of ferrofluid droplets in magnetic field ambience. Physics of Fluids, 32(8), 082001.
24. Mudra Jadav, R. J. Patel, R. V. Mehta.(2017). Influence of magnetic field on evaporation of a ferrofluid droplet. Journal of Applied Physics, 122(14),1–8.
25. Saedi, M., Aminfar, H., Mohammadpourfard, M. et al.(2019). Simulation of ferrofluid flow boiling in helical tubes using two-fluid model. Heat Mass Transfer, 55, 133–148.
<https://doi.org/10.1007/s00231-018-2400-9>
26. Mohammadpourfard, M., Aminfar, H. & Sahraro, M.(2014). Numerical simulation of nucleate pool boiling on the horizontal surface for ferrofluid under the effect of non-uniform magnetic field. Heat Mass Transfer, 50, 1167–1176.
27. Shyam Sudip,Mondal Pranab Kumar,Mehta Balkrishna.(2020). Field driven evaporation kinetics of a sessile ferrofluid droplet on a soft substrate. Soft matter,16(28), 6619–6632.

Figures

Figure 1

Ferrofluid in a vessel with a hole.

Figure 2

Ferrofluid in a test tube.

Figure 3

Sample in a high temperature test chamber.

Figure 4

Weighing with precision electronic balance.

Figure 5

The weight loss of samples and their fitted curves at different temperatures.

Figure 6

The prediction of evaporation rate for ferrofluid at different temperatures.

Figure 7

The weight loss of samples and their fitted curves with different dilution rate.

Figure 8

The prediction of evaporation rate for ferrofluid with different dilution rate.

Figure 9

The weight loss of samples and their fitted curves with different height.

Figure 10

The prediction of evaporation rate for ferrofluid with different height.

Figure 11

The weight loss of samples and their fitted curves with and without a magnetic field.