RESEARCH ON CONVECTIVE HEAT TRANSFER CHARACTERISTICS OF Fe_3O_4 MAGNETIC NANOFLUIDS UNDER VERTICAL MAGNETIC FIELD

by

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This paper focuses on the convective heat transfer characteristics of Fe_3O_4-water magnetic nanofluids under laminar and turbulent conditions. After verifying the accuracy of the experimental apparatus, the effects of magnetic field strength, concentration, Reynolds number and temperature on the convective heat transfer coefficient have been studied. The convective heat transfer characteristics of nanofluids under laminar and turbulent flow conditions were studied in depth, and the influence of each factor on the heat transfer coefficient was analyzed by orthogonal experimental design method. Under the laminar flow conditions, the convective heat transfer of magnetic nanofluids performed best when the Reynolds number was 2000, the magnetic field strength was 600, the temperature was 30 °C, and the concentration was 2%. The convective heat transfer coefficient, h, increased by 3.96% than the distilled water in the same conditions. In turbulent state, the convective heat transfer of magnetic nanofluids performed the best when the Reynolds number was 6000, the magnetic field strength was 600, the temperature was 40 °C, and the concentration was 2%. The h increased by 11.31% than the distilled water in the same Reynolds number and the magnetic field strength conditions.

Key words: *Fe_3O_4 -water magnetic nanofluids, orthogonal-experiments, magnetic field, heat transfer characteristics*

Introduction

In recent years, many studies focused on the medium of natural-convection and increase of thermal conductivity of a working medium to increase the heat transfer efficiency in order to achieve excellent heat transfer coefficients with a low cost and environmentally friendly manner [1]. As a common heat transfer conductor, fluids are mainly used in vehicle and avionics refrigeration system, solar thermal collection system, and liquid cooling system of chip heat dissipation [2]. However, the thermal conductivity of solid particles is much better than that of traditional fluids. The addition of nanoparticles can change of the coefficient of thermal conductivity, viscosity and surface tension of thermal physical property parameters, effectively improve the coefficient of thermal conductivity of liquid, the strengthening heat transfer performance of liquid. Therefore, the combination of solid particles and traditional fluids have become a research hotspot for researchers at home and abroad [3].

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Magnetic nanofluids (MNF) are a new class of heat transfer fluids that can be prepared by dispersing superparamagnetic nanoparticles with a typical diameter of less than 20 nm in base fluids such as water, oil, ethylene glycol*, etc.* The MNF exhibit both the fluid and magnetic properties [4]. Nanoparticles used in these nanofluids include metallic materials such as iron, nickel, cobalt, and their oxides such as magnetite (Fe_3O_4). When the magnetic field is applied, the distribution structure characteristics of the particles change, which makes the thermal properties of MNF change [5]. Compared with ordinary liquid working medium, it is not only a matter has excellent thermal properties, such as magnetic coefficient of thermal conductivity of nanofluids increases significantly, the heat transfer effect enhances obviously. Moreover, some of its thermal property parameters, such as viscosity, density, specific heat, thermal conductivity, and diffusion coefficient, will also change with the strength and direction of the applied magnetic field [6]. Thus, MNF become a *controlled* heat and mass transfer medium which can meet the requirements of high efficiency and high load heat and mass transfer.

Various experiments and simulations have been carried out to evaluate the flow and heat transfer of a nanofluids since the closest period of time. For instance, Zheng *et al.* [7] studied the laminar convection heat transfer of ferromagnetic fluids with different concentrations (1.25~2.5%) under the conditions of constant and alternating magnetic fields, and found that under the action of alternating magnetic fields, the convective heat transfer coefficient increased by 19.8% at most. Mei *et al.* [8] established an experimental system for convective heat transfer characteristics of MNF Fe_3O_4-water, studied the influence of external magnetic field, magnetic field intensity, magnetic field direction, fraction of nanoparticles, axial ratio and other factors on convective heat transfer coefficient of MNF. The experimental results show that the convective heat transfer coefficient increases with the increase of magnetic field strength. When the direction of magnetic field is consistent with the direction of fluid motion, the external magnetic field intensifies the convective heat transfer process. Sha *et al.* [9] conducted a detailed experimental study on convective heat transfer of Fe_3O_4-water nanofluids with a volume fraction of 3% under the action of uniform magnetic field and gradient magnetic field with different temperature, different magnetic field size and direction. It was found that the average convective heat transfer coefficient of the nanofluids laminar flow increased by 5.2% under the vertical uniform magnetic field. The average convective heat transfer coefficient of the nanofluids decreased by 4.8% under the horizontal uniform magnetic field.

Previous researchers adopted the combination of nanofluids and magnetic field to improve the heat transfer, which promotes the heat transfer enhancement technology. However, the comprehensive influence of the magnetic field strength, concentration, Reynolds number and temperature on the convective heat transfer coefficient was seldom discussed. So in this paper the convective heat transfer characteristics of Fe_3O_4-water nanofluids under laminar and turbulent flow conditions were studied in depth, and the influence of each factor on the heat transfer coefficient were analyzed by orthogonal experimental design method. In addition, the formulas and experimental methods of various factors that are valuable for industrial application can be obtained for reference.

Experimental set-up

The experimental bench is shown in fig. 1. The flow circulation system is consists of the experimental test section, data acquisition section and heat dissipation section. Experimental section is consists of a root length 500 mm, tube diameter is 14 mm, 2 mm thick wall copper tube, pipe external uniform package 220 V and 150 W of aluminum foil heating tablets, after electrify by aluminum foil temperature, and tube ferroferric oxide nanofluids flows between convective heat transfer, by adjusting the power change the heating power so as to meet the experiment requirement, respectively. The insulation cottons are wraped outside the heating section reduce the heat loss. The MNF is powered by a pump (14000 Lph), and the flow is adjusted through a valve. The inlet and outlet are measured by customized *K*-type thermocouple. In the test section, seven *T*-type thermocouple connection data acquisition instruments are automatically recorded. Three of the thermocouple positions are provided with NdFeb permanent magnets to provide a vertical magnetic field. The magnetic field strength is measured by gm-2A Gauss meter. In the experiment, the flow rate was reached by adjusting the valve, and the experimental data were collected by using the recording pressure gauge, flow meter and data acquisition instrument. In addition, in order to ensure the accuracy of the experimental data, 3 data were measured in the experiment for the same working condition.

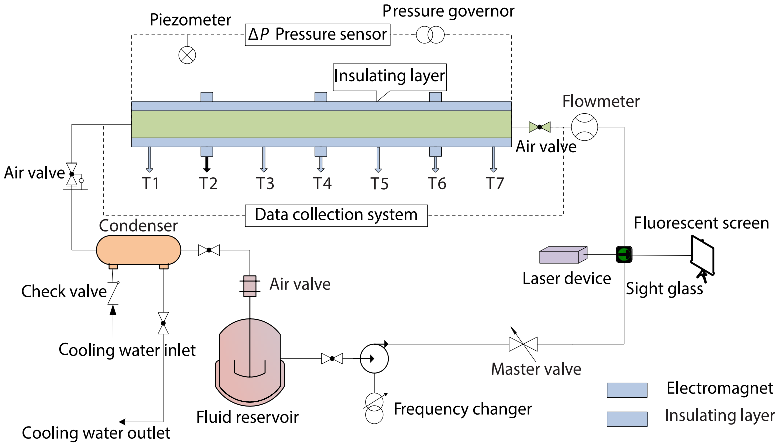

Figure 1. The experimental bench of Fe_3O_4-water nanofluids

The preparation of nanofluids can be divided into one-step and two-step methods [10]. The one-step method is to prepare nanofluids in one step and distribute them evenly in the fluid while synthesizing nanoparticles. The two-step method involves the synthesis of nanoparticles firstly, which are dispersed in the liquid, and the stability of the nanofluids is maintained by the dispersant [11].

The Fe_3O_4 -water nanofluids was prepared by two-step method after considering economic and other factors seriously. The mass fraction of the nanoparticles in prepared nanofluids samples were 0.5 wt.%, 1 wt.%, 1.5 wt.%, and 2wt.%, respectively. The addition of dispersant sodium dodecyl benzene sulfonate (SDBS) can slow down the deposition of nanoparticles to a certain extent, playing a good dispersion effect. The weighed Fe_3O_4 nanoparticles were dispersed into distilled water firstly, and then the dispersant SDBS (the weight was as same as the nanoparticles) was added to the mixture. After the formulation of nanofluids, the 90 minutes ultrasonic agitation (CP-3010GTS, 40 KHz) and 30 minutes magnetic stirring (JKI, 200-1500 rpm) are conducted for each sample to improve the stability, then took out for subsequent experiments.

3 Data processing formula

Validation of convective heat transfer experimental set-up

The following is the calculation formula of the average convective heat transfer coefficient of the pipe surface [12]:

$$h(x)=\frac{Q}{T_s(x)-T_m(x)} \tag{1}$$

where h is the convection heat transfer coefficient, Q – the constant heat flux applied to the copper tube, $T_s(x)$ and $T_m(x)$ are surface temperature and volume fluid temperature, respectively, and $T_s(x)$ – measured at the surface temperature of the tube:

$$T_m(x)=\frac{qx}{L\dot{m}C_p}+T_{mi} \tag{2}$$

where L is the heating section length of the tube, $\dot{m}$ – the mass-flow rate, q – the total heat flow, T_{mi} – the inlet temperature of the fluid, and C_p – the surface heat flux of the fluid's specific heat capacity at constant pressure:

$$Q=\frac{\dot{m}C_p\left(T_{mi}-T_{m_0}\right)}{A} \tag{3}$$

The calculation formula of the average Nusselt number of experimental values:

$$\mathrm{Nu}_{\exp}=\frac{h_{\exp}D}{k} \tag{4}$$

where k is the thermal conductivity of nanofluids and D – the pipe diameter.

According to the pipe diameter, the Reynolds number of nanofluids is calculated:

$$\mathrm{Re}=\frac{\rho_{\mathrm{nf}}U_{\mathrm{nf}}D}{U_{\mathrm{nf}}} \tag{5}$$

where Re is the Reynolds number of nanofluids, U_{nf} – the velocity of the nanofluids, and D – the pipe diameter.

Uncertainty analysis

In the experiment, the uncertainty data may result from measurement errors such as heat flux or temperature equivalence [13]. The uncertainty calculation formulas of convective heat transfer coefficient, Reynolds and Nusselt numbers, and flow resistance coefficient:

$$h=\sqrt{\left(\frac{\partial h}{\partial u}\Delta U\right)^2+\left(\frac{\partial h}{\partial T_h}\Delta T_h\right)^2+\left(\frac{\partial h}{\partial T_{\mathrm{in,nf}}}\Delta T_{\mathrm{in,nf}}\right)^2+\left(\frac{\partial h}{\partial T_{\mathrm{out,nf}}}\Delta T_{\mathrm{out,nf}}\right)^2} \tag{6}$$

$$\mathrm{Re}=\sqrt{\left(\frac{\partial \mathrm{Re}}{\partial U}\Delta U\right)^2} \tag{7}$$

$$\Delta\mathrm{Nu}=\mathrm{Nu}\sqrt{\left(\frac{\Delta Q_r}{Q_r}\right)^2+\left(\frac{\Delta T}{T}\right)^2} \tag{8}$$

In this paper, the uncertainty values of all measured conditions have been calculated. The average uncertainty of the convective heat transfer coefficient was ±3.2%, the Reynolds number of nanofluids was ±5%, and the Nusselt number of nanofluids was ±2.14%.

Study on heat transfer characteristics of magnetic nanofluids

Verification of experimental system

The convective heat transfer characteristics of MNF under the action of an external magnetic field were studied by a convective heat transfer test system. At first the heat transfer performance of deionized water in laminar flow and turbulent state was tested, which the boundary value of laminar and turbulence flow determined to be 2300. The measured Nusselt number was compared with Sieder and Dnielinski models [14]. The results are shown in the following fig. 2. In laminar flow state, the experimental results fig. 2(a) and Sieder model fit well; and in turbulent state fig. 2(b), the experimental results are consistent with Dnielinski model. The afrementioned data has showed that the experimental bench has high stability.

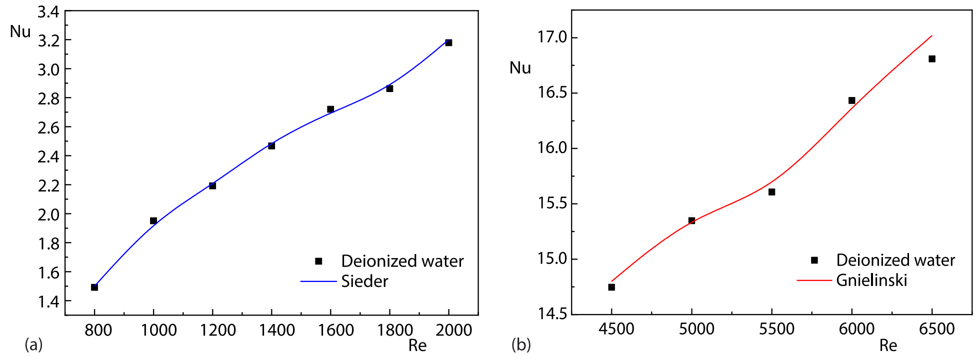

Figure 2. Verification diagram of deionized water on the convective heat transfer test bench

Effect of concentration on heat transfer coefficient of magnetic nanofluids

The fig. 3 shows the relationship between Reynolds number and convective heat transfer coefficient for different concentrations of MNF with B = 800 G (liquid temperature is 30 °C). It can be seen from the figure that the convective heat transfer coefficient increases with the increase of concentration, and the convective heat transfer is slow at low concentration. According to fig. 3(a), the convective heat transfer coefficient increases by 0.49%, 1.68%, 1.98%, and 3.12%, respectively, at Reynolds number of 800 and mass concentration of 0.5%, 1%, 1.5%, and 2%. At Reynolds number of 1600, the convective heat transfer coefficient increases by 2.75%, 3.67%, 4.77%, and 5.04%, respectively, when the mass concentration is 0.5%, 1%,

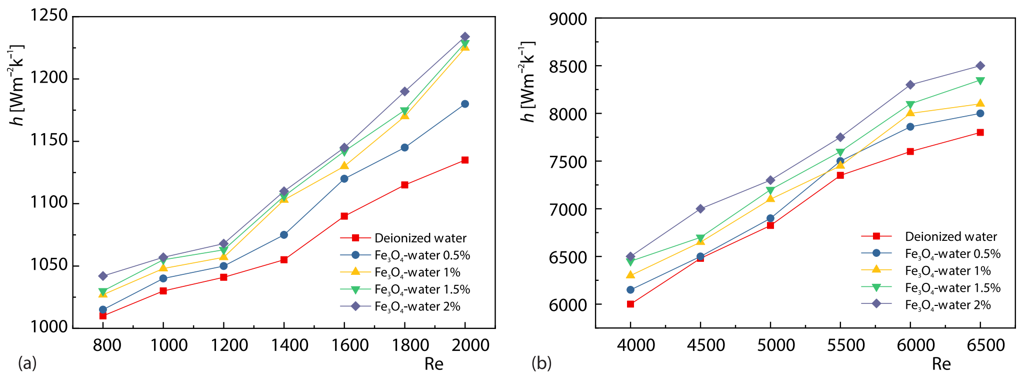

Figure 3. Relationship between concentration and convective heat transfer coefficient of MNF; (a) laminar flow zone and (b) turbulent zone

1.5%, and 2% at Reynolds number 1600. As shown in fig. 3(b), when the volume concentration was 0.5%, the MNF increased by 2.01% compared with deionized water, and the increase of convective heat transfer in the tube was not significant. When the mass concentration is 1%, 1.5%, and 2%, the convective heat transfer coefficient increases by 5%, 7.56%, and 12.91%, respectively at the Reynolds number of 6000.

It is well-known that the higher the concentration of MNF, the better the heat transfer performance. This is due to the increase of the volume concentration of MNF, resulting in the formation of longer and more chain like structures, and the convective heat transfer is significantly affected by the thermal conductivity and viscosity [15]. The increase of thermal conductivity enhances the convective heat transfer coefficient of nanofluids, but the increase of viscosity increases the thickness of thermal boundary-layer and hinders the convective heat transfer of MNF. When the concentration of nanoparticles increases to a certain extent, the particles agglomerate, leading to the increase of the thickness of the boundary-layer, and even adsorb on the wall of the tube [16]. Therefore, when the volume concentration is between 0.5% and 2%, the convective heat transfer coefficient of MNF increases with the increase of concentration, which is caused by the increase of thermal conductivity.

Effects of different temperatures on heat transfer coefficient of magnetic nanofluids

The relationship between convective heat transfer coefficient, h, and Reynolds number at 20 °C, 30 °C, and 40 °C (liquid temperature) is shown in fig. 4. It can be seen that the convective heat transfer coefficient increases with the increase of temperature. As shown in fig. 4(a) in laminar state, when the Reynolds number was 800, the convective heat transfer coefficient at 30 °C and 40 °C increased by 1.38% and 2.96%, respectively, for the MNF with mass concentration of 1% and magnetic field strength of B = 800 G. When the Reynolds number was 1600, the convective heat transfer coefficient increased by 2.95% and 8.39%, respectively. According to fig. 4(b) in turbulent state, the convective heat transfer coefficient increased by 4.68% and 6.11% at 30 °C and 40 °C on average when the Reynolds number was 4000. The convective heat transfer coefficient increased by 6.07% and 8.28%, respectively, when the Reynolds number was 6000. This is because the boundary-layer thickness of the thermal motion of nanoparticles diffuses more strongly with the increase of temperature [17], and the convective heat transfer coefficient increases with the temperature.

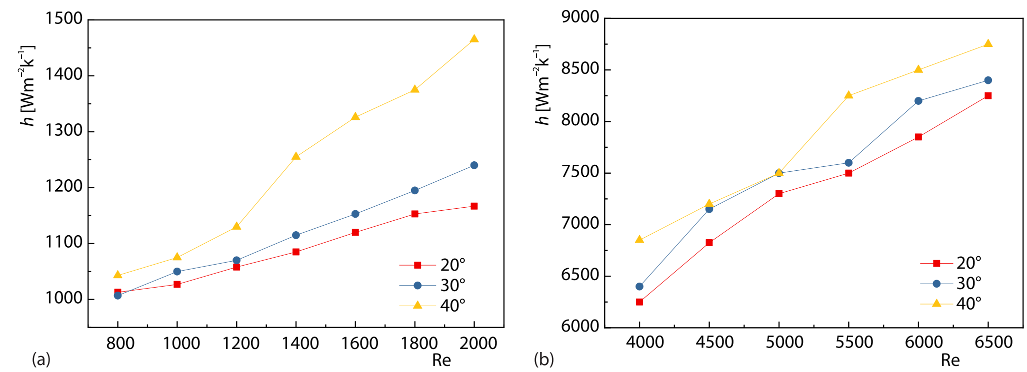

Figure 4. Relationship between temperature and convective heat transfer coefficient of MNF; (a) laminar flow zone and (b) turbulent zone

Effect of external magnetic field on heat transfer coefficient of magnetic nanofluids

As shown in fig. 5, the relationship between convective heat transfer coefficient and Reynolds number is compared between MNF (with mass concentration of 1% at room temperature) and deionized water in laminar and turbulent flow states. As shown in fig. 5(a) in the laminar flow state, the convective heat transfer coefficient of MNF is higher than that of deionized water when there is no external magnetic field. The convective heat transfer coefficient increases by 5.54% when the Reynolds number is 1000 and 15.87% when the Reynolds number is 1800. When an external magnetic field was added (the magnetic field strength was 800 *G*), the heat transfer coefficient was significantly higher than that without an external magnetic field. When the Reynolds number was 1600, the convective heat transfer coefficient increased by 46.92% compared with that of deionized water and 61.18% compared with that of MNF. In general, in the case of magnetic field addition, the heat transfer coefficient increases by 17.25% on average compared with ordinary MNF (when the Reynolds number is less than 1000, the presence or absence of magnetic field has little influence on the heat transfer coefficient).

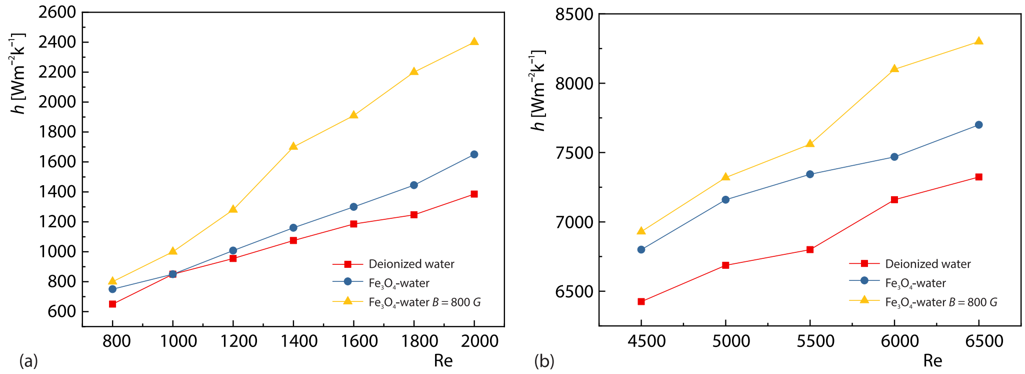

Figure 5. Relationship between the external magnetic field and the convective heat transfer coefficient of MNF; (a) laminar flow zone and (b) turbulent zone

As shown in fig. 5(b) in the turbulent state, while there is no external magnetic field, the convective heat transfer coefficient of MNF is higher than that of deionized water, which increases by 8.73% when the Reynolds number is 4000, with an average increase of 12.07%. When an external magnetic field was added, the convective heat transfer coefficient was significantly higher than that nanofluids without an external magnetic field, and the convective heat transfer coefficient increased by an average of 61.94% compared with that of deionized water and average of 27.17% compared with that of MNF.

It can be seen from fig. 5 that the heat transfer coefficient in the turbulent state is higher significantly. First of all, the addition of nanoparticles changes the heat transfer phenomenon inside the liquid, aggravating Brownian motion and hot swimming motion inside the liquid, further disturbing the thermal boundary-layer, and enhancing the convective heat transfer under laminar and turbulent conditions finally [18]. Secondly, under the influence of turbulent vortices, the motion of nanoparticles is influenced by turbulent vortices in the turbulence, which enhances the ability of mixing and heat transporting. Therefore, the convective heat transfer is enhanced slightly [19]. After the addition of an external magnetic field, Fe_3O_4 nanoparticles are affected by the magnetic field, and particle aggregation and agglomerate formation occur near the magnet (leading to the improvement of local thermal conductivity) [20]. The previous phenomenon plays a role of energy transfer and momentum enhancement in the flow, further enhancing the convective heat transfer effect.

Influence of magnetic field strength on heat transfer coefficient of magnetic nanofluids

As shown in fig. 6, under the effect of B = 0, 200, 300, 600, 800, and 1000 G vertical magnetic field, the convective heat transfer coefficient of MNF (with mass concentration of 1% at room temperature) increased with the increase of Reynolds number, and the increase was more obvious after the magnetic field intensity $B \geq 600$ G. It can be seen from fig. 6(a) in the laminar flow state, when the Reynolds number is 1000, the magnetic field intensity $B = 300$ G and $B = 0$ G increased by 2.53% compared to the convective heat transfer coefficient. When the magnetic field intensity B = 600, 800, and 1000 G, the convective heat transfer coefficient increased by 4.67%, 5.25%, and 5.33%, respectively. It can be seen from fig. 6(b) in the turbulent state, when B = 0, 200, and 300 G, the convective heat transfer coefficient of the MNF changed gently with the Reynolds number, while the convective heat transfer coefficient does not increase significantly (when $B = 300$ G, it only increased by 3.77% compared with that $B = 0$ G). When the magnetic field intensity $B = 600$ G, the convective heat transfer coefficient increased with the increase of the magnetic field intensity significantly. When the Reynolds number is 5000, the convective heat transfer coefficient increased by 9.23%, 18.85%, and 23.08%, respectively when the magnetic field intensity B= 600, 800, and 1000 G. When the Reynolds number is 6500, the convective heat transfer coefficient increased by 16.90%, 22.54%, and 26.06%, respectively.

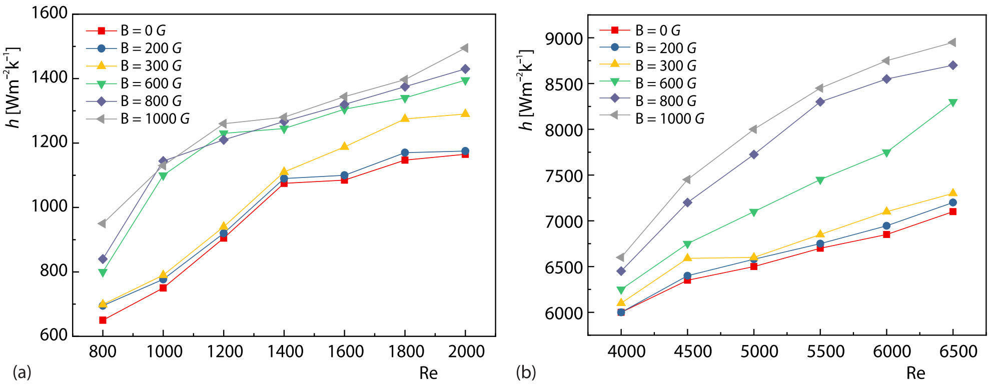

Figure 6. Relationship between magnetic field strength and convective heat transfer coefficient of MNF; (a) laminar flow zone and (b) turbulent zone

The analysis shows that the setting of the magnetic field and the increasing of the magnetic field strength lead to the vortex generated by the magnetic field source destroyed the boundary-layer, which enhances the heat transfer efficiency [21]. When the MNF passes through the magnet, the magnetic nanoparticles are attracted to the surface of the tube, which due to the magnetic distribution [22]. The migration of the nanoparticles to the surface of the tube leads to an increase in the concentration of local particles on the surface of the tube, and then the heat can be transferred to the nanoparticles, leading to an enhance in the local thermal conductivity. In addition, when magnetic force (not the heat), has a significant impact on magnetic nanoparticles, particles stick together and form chains oriented along the direction of the applied field, and particles form coupling, triplet and short chains in the direction of the external magnetic field, at last improving the thermal conductivity [23]. On the other hand, the accumulation of particles near the surface of the pipe leads to the increase of friction on the surface of the pipe, which disturbs the flow pattern and thermal boundary-layer, further increases the local convective heat transfer.

Analysis of factors affecting convective heat transfer

In order to further understand the influence of concentration, Reynolds number, temperature and magnetic field strength on MNF, orthogonal experiments at the level of L9 (34) were designed. The horizontal table of factors and orthogonal experimental designs in laminar flow state are shown in tabs. 1 and 2, and the effect curve was shown in fig. 7.

Table 1. Table of factors in laminar flow state

Serial number	Reynolds number	Magnetic field intensity [GS]	Temperature [°C]	Concentration [%]
1	1000	0	20	0.5
2	1400	600	30	1
3	2000	1000	40	2

Table 2. Table of orthogonal test in laminar flow state

Serial number	Reynolds number A	Magnetic field intensity [GS] B	Temperature [°C] C	Concentration [%] D	Heat transfer coefficient, h
1	1	1	1	1	937
2	1	2	2	2	1104
3	1	3	3	3	1083
4	2	1	1	1	1169
5	2	2	2	2	1245
6	2	3	3	3	1202
7	3	1	1	1	1237
8	3	2	2	2	1502
9	3	3	3	3	1392
K_1 (Mean value)	1041.333	1114.333	1213.667	1191.333	–
K_1 (Mean value)	1205.333	1283.667	1221.667	1181.000	–
K_1 (Mean value)	1377.000	1225.667	1188.333	1251.333	–
Range, R	335.667	169.334	33.334	70.333	–
Deionized water	–	–	–	–	1463
Best formula	2000	600 G	30 °C	2%	1521

As the number of different levels of each factor is sometimes different, the average value is generally used to reflect the impact of different levels of the same factor on the test results, and the optimal level of this factor should be determined accordingly. The range Reynolds number of the average quantity at each level of the same factor is used to reflect the influence of the level change of each factor on the test results. A large range means that the variation of the level of the factor has a great impact on the test results, while a small range means that the varia-

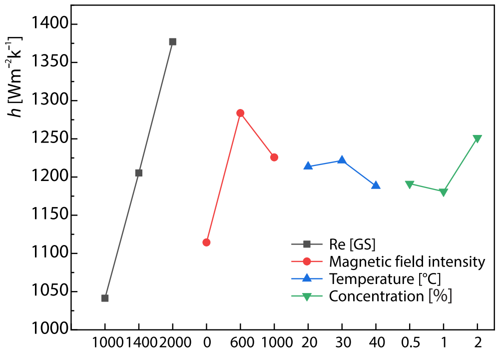

Figure 7. Effect graph in laminar flow state

tion of the level of the factor has a small impact on the test results. According to the range in the orthogonal experimental table under laminar flow state, $C < D < B < A$ is temperature, concentration, magnetic field strength and Reynolds number in turn, of which Reynolds number has the greatest influence. Contrast laminar state the mean of orthogonal experiment table, the optimal levels are A_3, B_2, C_2, and D_3. According to the mean values in orthogonal tab. 2 in laminar flow state, the optimal combination is $A_3B_2C_2D_3$. As can be seen from the fig. 7 effect graph, when the Reynolds number is 2000, the magnetic field strength is 600, the temperature is 30 °C and the concentration is 2%, the convective heat transfer effect of magnetic nanofluids is the best. Specifically, the convective heat transfer coefficient (h = 1521) increases by 3.96% than the distilled water (h = 1463) in the same Reynolds number and the magnetic field strength conditions.

The factor level table and orthogonal experimental design under the turbulence state are shown in tabs. 3 and 4, and the effect curve is shown in fig. 8. According to the range difference in the orthogonal experimental table in the turbulent state, $C < D < B < A$ is temperature, concentration, magnetic field strength and Reynolds number in turn, of which Reynolds number has the greatest influence. By comparing the mean values in the orthogonal experimental table in the turbulent state, it can be seen that the optimal levels are A_3, B_2, C_3, and D_3, and the optimal combination is $A_3B_2C_2D_3$ according to the mean values in the orthogonal tab. 4 in the turbulent state. As can be seen from the effect curve in fig. 8, the convective heat transfer effect of MNF behave the best when the Reynolds number is 6000, the magnetic field strength is 600, the temperature is 40 °C and the concentration is 2%. And the convective heat transfer coefficient (h = 8364) increases by 11.31% than the distilled water (h = 7514) in the same Reynolds number and the magnetic field strength conditions.

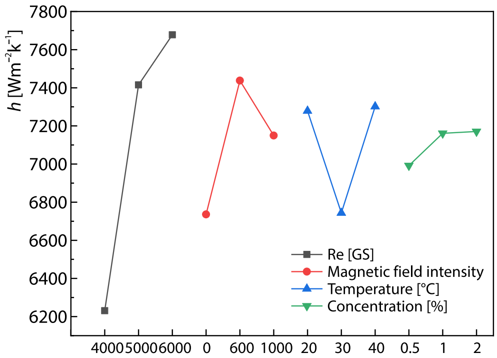

Figure 8. Effect graph in turbulent state

Conclusion

In this paper, two-step method was used to prepare stable Fe_3O_4-water nanofluids. The convective heat transfer characteristics of MNF in laminar and turbulent under vertical magnetic fields are studied.

Firstly, the accuracy of the experimental device is verified, and the effects of concentration, temperature and magnetic field intensity on the convective heat transfer coefficient are studied. Then, the convective heat transfer of MNF under the action of a vertical magnetic field was designed by using orthogonal experimental design method. Through the analysis of orthogonal table and effect curve, it can be concluded that Reynolds number has the greatest influence on the convective heat transfer coefficient, followed by magnetic field strength, concentration and temperature.

Table 3. Table of factors in turbulent state

Serial number	Reynolds number	Magnetic field intensity [GS]	Temperature [°C]	Concentration [%]
1	4000	0	20	0.5
2	6000	600	30	1
3	5000	1000	40	2

Table 4. Table of orthogonal test in turbulent state

Serial number	Reynolds number *A*	Magnetic field intensity [GS] *B*	Temperature [°C] *C*	Concentration [%] *D*	Heat transfer coefficient, *h*
1	1	1	1	1	5913
2	1	2	2	2	6250
3	1	3	3	3	6529
4	2	1	1	1	6742
5	2	2	2	2	7823
6	2	3	3	3	7681
7	3	1	1	1	7553
8	3	2	2	2	8241
9	3	3	3	3	7239
K_1 (Mean value)	6230.667	6736.000	7278.33	6991.667	–
K_2 *(Mean value)*	7415.333	7438.000	6743.667	7161.333	–
K_3 (Mean value)	7677.667	7149.667	7301.667	7170.667	–
Range, *R*	1447.000	702.00	558.00	179.000	–
Deionized water	–	–	–	–	7514
Best formula	6000	600 *G*	40 °C	2%	8364

Under the laminar flow conditions, the convective heat transfer of MNF performed best when the Reynolds number is 2000, the magnetic field strength is 600, the temperature is 30 °C and the concentration is 2%. Specifically, the convective heat transfer coefficient (h = 1521) increases by 3.96% than the distilled water (h = 1463) in the same Reynolds number and the magnetic field strength conditions. In turbulent state, the convective heat transfer of MNF performed the best when the Reynolds number is 6000, the magnetic field strength is 600, the temperature is 40 C and the concentration is 2%. In the same time, the convective heat transfer coefficient (h = 8364) increases by 11.31% than the distilled water (h = 7514) in the same Reynolds number and the magnetic field strength conditions.

It provides reliable experimental data support for future research on convective heat transfer characteristics of MNF in vertical magnetic field, and the idea of setting up the experimental bench can be used for reference by subsequent scholars, which is helpful to analyze the application prospect of MNF in industry.

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Nomenclature

A – area, [m^2]
B – magnetic field intensity, [G]
D – inside diameter of circular pipe, [m]
G – mass-flow density, [kgm^{-2}s^{-1}]
h – average heat transfer coefficient, [Wm^{-2}K^{-1}]
k – thermal conductivity of the tube, [Wm^{-1}K^{-1}]
L – length of the pipe, [m]
Nu – Nusselt number (= hL/k), [–]
P – pressure, [Pa]
Q – heating power, [W]
Re – Reynolds number (= UD/n), [–]
T – temperature, [K]
U – velocity, [ms^{-1}]

Reference

[1] Maxwell, J. C. A., A Treatise on Electricity and Magnetism, *Nature*, *182* (1981), 7, pp. 478-480
[2] Wang, B. X., Effect of Particle Agglomeration on Thermal Properties and Thermal Process of Low Concentration Nanofluids, *Journal of Mechanical Engineering*, *45* (2009), 3, pp. 1-4
[3] Qiu, L., *et al.*, A Review of Recent Advances in Thermophysical Properties at the Nanoscale: From Solid State to Colloids. *Physics Reports, 843* (2020), Feb., pp. 1-81
[4] Teng, A., *et al.*, The progress of magnetic nanomaterials in application of biomedicine. *Journal of Biomedical Engineering, 31* (2014), 2, 472
[5] Arora, N., *et al.*, An Updated Review on Application of Nanofluids in Flat Tubes Radiators for Improving Cooling Performance, *Renewable and Sustainable Energy Reviews, 134* (2020), 110242
[6] Chen, J., *et al.*, Effect of Nanoparticle Aggregation on the Thermal Radiation Properties of Nanofluids: An Experimental and Theoretical Study, *International Journal of Heat and Mass Transfer, 154* (2020), 119690.
[7] Zheng, Y., *et al.*, Sonication Time Efficacy on Fe_3O_4-Liquid Paraffin Magnetic Nanofluid Thermal Conductivity: An Experimental Evaluation, *Ultrasonics Sonochemistry, 64* (2020), 105004
[8] Mei, S., *et al.*, Effects of Paralleled Magnetic Field on Thermo-Hydraulic Performances of Fe_3O_4-Water Nanofluids in a Circular Tube, *International Journal of Heat and Mass Transfer, 134* (2019), May, pp. 707-721
[9] Sha, L., *et al.*, The Influence of the Magnetic Field on the Convective Heat Transfer Characteristics of Fe_3O_4-Water Nanofluids, *Applied Thermal Engineering, 126* (2017), Nov., pp. 108-116
[10] Ambreen, T., *et al.*, Influence of Particle Size on the Effective Thermal Conductivity of Nanofluids: A Critical Review, *Applied Energy, 264* (2020), 114684
[11] Chen, P., *et al.*, Research on Heat Transfer Characteristics of Flow in Tube of Water-Based Nanofluids, *Thermal Science, 25* (2020), 5A, pp. 3505-3515
[12] Putra, N., *et al.*, Natural-Convection of Nanofluids, *Heat and Mass Transfer, 39* (2003), 8-9, pp. 775-784
[13] Tong, Y., *et al.*, Improvement of Photo-Thermal Energy Conversion Performance of MWCNT/Fe_3O_4 Hybrid Nanofluid Compared to Fe_3O_4 Nanofluid, *Energy, 196* (2020), 117086
[14] Nurdin, I., *et al.*, Enhancement of Thermal Conductivity and Kinematic Viscosity in Magnetically Controllable Maghemite (γ-Fe_2O_3) Nanofluids, *Experimental Thermal and Fluid Science, 77* (2016), *77*, pp. 265-271
[15] Olfian, H., *et al.*, Development on Evacuated Tube Solar Collectors: A Review of the Last Decade Results of Using Nanofluids, *Solar Energy, 211* (2020), Nov., pp. 265-282
[16] Anwar, M., *et al.*, Numerical Study for Heat Transfer Enhancement Using CuO-Water Nanofluids through Mini-Channel Heat Sinks for Microprocessor Cooling. *Thermal Science, 24* (2020), 5A, pp. 2965-2976
[17] Ajeel, R., *et al.*, Analysis of Thermal-Hydraulic Performance and Flow Structures of Nanofluids Across Various Corrugated Channels: An Experimental and Numerical Study, *Thermal Science and Engineering Progress, 19* (2020), Oct., 100604
[18] Cao, P., *et al.*, Role of Base Fluid on Enhancement Absorption Properties of Fe_3O_4-Ionic Liquid Nanofluids for Direct Absorption Solar Collector, *Solar Energy, 194* (2019), 1, pp. 923-931
[19] Ledari, B. H., *et al.*, An Experimental Investigation on the Thermo-Hydraulic Properties of CuO and Fe_3O_4 Oil-Based Nanofluids in Inclined U-tubes: A Comparative Study, *Powder Technology, 379* (2021), Feb., pp. 191-202

[20] Molana, M., *et al.*, Investigation of Hydrothermal Behavior of Fe_3O_4-H_2O Nanofluid Natural-Convection in a Novel Shape of Porous Cavity Subjected to Magnetic Field Dependent (MFD) Viscosity, *Journal of Energy Storage, 30* (2020), 101395
[21] Dehkordi, R. B., *et al.*, Molecular Dynamics Simulation of Ferro-Nanofluid-Flow in a Micro-Channel in the Presence of External Electric Field: Effects of Fe_3O_4 Manoparticles, *International Communications in Heat and Mass Transfer, 116* (2020), 104653
[22] Shin, Y., *et al.*, Magnetic Effect on the Enhancement of Photo-Thermal Energy Conversion Efficiency of MWCNT/Fe_3O_4 Hybrid Nanofluid, *Solar Energy Materials and Solar Cells, 215* (2020), 110635
[23] Sun, B., *et al.*, The Effect of Constant Magnetic Field on Convective Heat Transfer of Fe_3O_4-Water Magnetic Nanofluid in Horizontal Circular Tubes, *Applied Thermal Engineering, 171* (2020), 114920

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