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# STUDY ON MAGNETIC FLUID CONVECTION HEAT TRANSFER

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**Abstract:** This paper reviews the experimental research and numerical calculation results of magnetic fluid in the field of convection heat transfer in recent years, and analyzes and summarizes the experimental and calculation results; respectively explains the nanometer-scale technology in the research on magnetic fluid natural convection heat transfer and magnetic fluid forced convection heat transfer. The influence of fluid volume fraction, Rayleigh number, magnetic field strength and direction on convective heat transfer; finally, the existing problems and future research directions in magnetic fluid research are summarized.
**Keywords:** Magnetic fluid; Convection heat transfer; Numerical calculation; Experimental research

## 1 RESEARCH ON FORCED CONVECTION HEAT TRANSFER OF MAGNETIC FLUID

with a diameter of less than 20 nm in basic fluids such as water, ethylene glycol and other solutions. It is widely used in heat exchange. areas such as cooling system components. Magnetic fluid has both magnetic properties and fluidity. To prevent aggregation due to interactions between nanoparticles, suspended nanoparticles are usually covered with insoluble surfactants. In terms of using nanofluid to improve heat transfer performance, enhanced heat transfer technology is one of the most typical representative technologies. With the research on convection heat transfer technology becoming more and more in-depth, the industry has become more and more demanding on the use conditions of heat exchange equipment, and the requirements for heat exchange systems are also increasing. In recent years, the technology of external magnetic field enhancement and control of nanomagnetic fluid heat transfer has been greatly developed, and the application of magnetic fluid in heat transfer has attracted widespread attention.

### 1.1 Experimental Study

Li Qiang et al. [1] used $Fe_3O_4$ -water magnetic fluid to conduct experiments and studied the heat transfer characteristics of the magnetic fluid flowing through the heating filament. It was found that when the fluid flow is in the same direction as the magnetic field, the heat exchange between the fluid and the filament is enhanced. On the contrary, applying a magnetic field opposite to the flow will weaken the heat exchange between the two. Lajvardi et al. [2] studied $Fe_3O_4$ in heating copper tubes. Convective heat transfer characteristics of water nanofluid, the effects of magnetic nanoparticle concentration and magnet position on heat transfer were studied. The results show that by increasing the magnetic field and magnetic fluid concentration, the Nusselt number can be significantly increased, which is attributed to the significant changes in the thermal properties of the magnetic fluid under the influence of the magnetic field. Ghofrani et al. [3] studied magnetic fluid convection heat transfer under alternating magnetic fields. The results show that in the absence of a magnetic field, the magnetic fluid enhances the average convective heat transfer along the copper tube, and the local heat transfer enhancement effect is more significant at a shorter distance from the entrance area and at a higher volume concentration. Applying a constant magnetic field at the axial distance from the inlet has an adverse effect on heat transfer or the enhancement is weak. Under an alternating magnetic field, when the Reynolds number is 80, the average heat transfer increases by 26. 38% to 28. 82%. In addition, the alternating magnetic field is more effective at high frequencies and high volume concentrations, and the magnetic effect is not obvious at lower volume concentrations. Wu Zhijiang et al. [4] analyzed the heat transfer of $Fe_3O_4$-water magnetic fluid in copper tubes. The results show that the heat transfer intensity increases with the increase of the magnetic field strength; the heat transfer process is enhanced when the fluid flows along the direction of the magnetic field, especially when the fluid flows at low flow speed, the heat transfer enhancement is more significant. Yarahmadi [5] studied ferrofluid laminar heat transfer under constant and oscillating magnetic fields. The results show that in a magnetic field-free environment, compared with distilled water, the heat transfer of magnetic fluid is enhanced. In addition, using an oscillating magnetic field, the convective heat transfer of the circular tube increases, with a maximum enhancement of 19.8%. The application of a constant magnetic field has a counterproductive effect on the convective heat transfer, resulting in reduced heat transfer. Goharkhah et al. [6] studied the convective heat transfer of $Fe_3O_4$-water magnetic fluid under external magnetic field. The results show that without magnetic field, magnetic fluid increases the maximum heat transfer intensity by 16. 4%. By applying constant and alternating magnetic fields, this value increases to 24. 9% and 37. 3% respectively. At a constant Reynolds number, as the magnetic field intensity increases, the heat exchange increases. Shahsavar et al. [7] studied constant and alternating magnetic field pairs containing tetramethylammonium hydroxide, $Fe_3O_4$ Effect of magnetic fluid forced convection heat transfer on nanoparticles and carbon nanotubes. The results show that under the condition of no magnetic field, the heat transfer of the system is significantly improved by using magnetic fluid. In the presence of constant and alternating magnetic fields, the heat transfer of magnetic fluids is improved, and the increase in heat transfer caused by the constant magnetic field is more significant than that of the alternating magnetic field, and in the magnetic fluid with higher volume concentration and lower Reynolds number , the influence of magnetic field on heat transfer is more significant. Mehrali et al.[8] studied the mixing of graphene/Fe3 O4 under the influence of magnetic field. Heat transfer in nanofluids. The results show that the thermal conductivity of the mixed fluid is enhanced by 11%, but in the absence of a magnetic field, the heat transfer enhancement of the mixed magnetite nanofluid is negligible compared with distilled water; the heat transfer characteristics are significantly improved under a magnetic field. Hatami et al. [9] studied the effect of magnetic field on forced convection heat transfer of $Fe_3O_4$-water nanofluid flowing through a circular tube under laminar flow. The results show that in the absence of a magnetic field, magnetic fluid increases heat transfer by more than 60%. Under a uniform magnetic field, the heat transfer effect decreases with the increase of nanoparticles. For a given concentration of magnetic nanofluid, the heat transfer rate is reduced by approximately 25% by increasing the Hartmann number.

To sum up, in the experimental study of forced convection of magnetic fluid, compared with the environment without magnetic field, the external magnetic field can significantly promote the heat transfer of magnetic fluid. When the magnetic fluid has a higher volume concentration and a lower Reynolds number, the magnetic field has the most significant impact on heat transfer. Using magnetic fluids to enhance heat transfer has great potential in a wide range of applications, but experimental results from different research groups lack consistency. In a constant or uniform magnetic field environment, magnetic fluid convection heat transfer is weakened. This may be attributed to the weakening of the Brownian motion of the nanoparticles due to the application of an external magnetic field. Therefore, more experiments are needed to determine the heat transfer characteristics of magnetic fluids in magnetic fields, and then determine the adaptability and generalization of magnetic fluid applications.

### 1.2 Numerical Simulation

Zhou Junjun [10] simulated the heat transfer of magnetic fluid under a magnetic field. Under the condition of uniform magnetic field, the heat transfer of magnetic fluid is suppressed, which is attributed to the aggregation of particles in the fluid weakening the heat transfer effect of the fluid. Under gradient magnetic field conditions, the magnetic field force increases the movement of particles and enhances heat transfer. Aminfar et al.[11] simulated and analyzed the relationship between kerosene and $Fe_3O_4$ in the presence of non-uniform magnetic field. Convection heat transfer characteristics of magnetic fluid composed of nanoparticles. The results show that under positive and negative gradient magnetic fields, the Nusselt number decreases and increases respectively. The gradient and intensity of the magnetic field determine the degree of change of the Nusselt number. Therefore, a magnetic field can be used to control the heat transfer coefficient. Aminfar [12] simulated the heat transfer of magnetic fluid in a bent tube under a magnetic field. The results show that the heat transfer coefficient can be increased by using bent tubes instead of straight tubes. When the magnetic field acts perpendicularly to the direction of the mainstream, it can increase the secondary flow in the elbow. As the magnetic field increases, the secondary flow increases, thereby enhancing heat transfer. Goharkhah et al. [13] simulated the behavior of magnetic fluid under an alternating non-uniform magnetic field. Heat transfer characteristics. The results show that compared with the case without magnetic field, the convective heat transfer of magnetic fluid can be significantly improved by applying an alternating magnetic field. Heat transfer becomes stronger as the Reynolds number and magnetic field strength become larger. At the same time, the increase in pressure drop is not as significant as the heat transfer enhancement. At a Reynolds number of 2000 and a frequency of 5 Hz, the maximum pressure drop increases by 6%. Azizian et al.[14] studied the effect of external magnetic field on heat transfer and pressure drop of magnetite nanofluid under laminar flow conditions. The results show that by increasing the magnetic field strength and gradient, the local heat transfer is significantly improved. The convective heat transfer enhancement becomes more pronounced at higher Reynolds numbers, at Re 745 and magnetic field gradient 32. 5 mT/mm When , a 4-fold enhancement was obtained (relative to the case without magnetic field). At the same time, the influence of the magnetic field on the voltage drop is not significant. When the field strength is 430 mT and the gradient is 8. 6 ~ 32. 5 mT/mm, the voltage drop only increases by 7. 5%. Ghasemian et al.[15] simulated $Fe_3O_4$ in microchannels under the action of magnetic field. Heat exchange in hydromagnetic fluids. The effect of constant magnetic field position and intensity on convective heat transfer was studied. The results show that the eddies generated by the magnetic field source destroy the boundary layer and lead to enhanced heat transfer, and this effect is more obvious when the magnetic field source is placed in a fully developed area. Under the action of a constant magnetic field strength, when Re is 25, the heat transfer is enhanced by 16. 48%. Under a magnetic field with the same intensity and frequency of 4 Hz, the value increases to 27. 72% at a lower Reynolds number. , the heat transfer enhancement caused by the magnetic field is more significant. Bahiraei et al. [16] studied the effect of linear dipole magnetic field on magnetic fluid heat transfer between two parallel plates. The results show that by applying a magnetic field, the local thermal convection heat transfer between the two walls increases. This is due to the magnetic field disrupting the boundary layer flow, resulting in enhanced mixing and more uniform temperature distribution, thereby enhancing convective heat transfer. The improvement in convective heat transfer is more significant for larger magnetic field strengths and lower Reynolds numbers. Fadaei et al[17] The three-dimensional forced convection heat transfer of magnetic fluid in the tube is simulated. It was found that as the field strength and current intensity of the permanent magnet increase, the heat transfer rate and Nusselt number increase, but the use of permanent magnets is more effective. It was found that by using single and dual permanent magnets, the fully developed segment Nusselt number was enhanced to 113% and 196%, respectively.

In summary, in the simulation studies of forced convection of magnetic fluid, most simulations indicate that the forced convection heat transfer of magnetic fluid can be significantly improved by applying an alternating magnetic field. As the magnetic field intensity increases, the forced convection heat transfer increases. Compared with a constant magnetic field, an alternating magnetic field improves convection heat transfer more significantly. Magnetic field strength and gradient have a great influence on convective heat transfer. Magnetic field gradient and strength determine the extent to which the Nusselt number increases or decreases. Therefore, the heat transfer coefficient can be controlled by the magnetic field, thereby controlling the rate and process of forced convection heat transfer. In addition, studies have shown that the magnetic field has a weak impact on the pressure drop during the heat exchange process (compared to its impact on the heat transfer effect).

## 2 RESEARCH ON NATURAL CONVECTION HEAT TRANSFER OF MAGNETIC FLUID

### 2.1 Experimental Study

Bednarz et al.[18] studied the influence of magnetic field on the natural convection of magnetic fluid in a cube. The results show that under strong magnetic field conditions, the intensity of natural convection can be increased and the direction of convection can be changed. Under a magnetic induction of 10 T, the magnetic force acts perpendicular to gravity, forming an almost horizontal convective circulation in the enclosure. Stoian et al.[19] studied the convection heat transfer of $Fe_3O_4$-hydromagnetic fluid in a cylindrical shell. Experimental results show that, under certain conditions, the natural convection heat transfer of nanofluids can be enhanced by an appropriate match between the device geometry, the thermal properties, flow properties and buoyancy of the nanofluids. Kim et al.[20] studied the natural convection heat transfer characteristics of magnetic fluid in concentric cylinders under a rotating magnetic field. The results show that the convective heat transfer intensity of magnetic fluid in a rotating magnetic field can be controlled by the number of revolutions and magnetic field intensity. As the rotation speed and magnetic field intensity increase, the convective heat transfer effect of magnetic fluid in concentric cylinders increases. Xu Chunlong[21] experimentally studied the convection heat transfer of magnetic fluid under magnetic gravity compensation. The results show that in the absence of a magnetic field, as the volume fraction of magnetic fluid increases, the Nusselt number of convection heat transfer decreases, indicating that the nanomagnetic particles added to the magnetic fluid cause its convection intensity to weaken; under a uniform magnetic field, compared with without a magnetic field Under certain conditions, the viscosity of the magnetic fluid increases and the heat transfer efficiency weakens; when the magnetic force and gravity are reversed, the natural convection of the magnetic fluid will be inhibited. By increasing the magnetic field force, the weakening effect of magnetic fluid convection is significant. Kraszewska et al. [22] experimentally analyzed the impact of strong magnetic fields on natural convection heat transfer of magnetic fluids, estimated the Nusselt number and performed spectral analysis of fluid behavior. It was found that the magnetic field has an important influence on magnetic fluid flow and heat transfer. Under the influence of a magnetic field, the movement of magnetic fluid intensifies, resulting in a significant increase in the Nusselt number.

To sum up, in the experimental study of natural convection of magnetic fluid, under the external magnetic field environment, the magnetic fluid can enhance the natural convection, strengthen the movement of the magnetic fluid through the magnetic field force, and thereby enhance the heat transfer. At the same time, the convective heat transfer process can also be suppressed, and the influence of gravity is offset by magnetic field force. The effective gravity acceleration is reduced, the Nusselt number is reduced, and convection is suppressed. The results show that the intensity and process of convective heat transfer can be controlled by controlling the intensity and direction of the magnetic field. Under normal gravity conditions without a magnetic field, adding magnetic nanoparticles to the base fluid also causes deterioration in convection heat transfer.

### 2.2 Numerical Simulation

Bahiraei et al. [23] simulated the natural convection of magnetic fluid under uneven magnetic fields. The results show that the magnetic force exerted by the magnetic field enhances the circulation of fluid in the cavity, which in turn enhances heat transfer between the wall and the nanofluid. As the magnetic field gradient becomes larger, the natural convection of the fluid in the cavity increases. Kefayati et al. [24] simulated the natural convection of magnetic fluid in a chute in the presence of an external magnetic field. The results show that for various Rayleigh numbers and tilt angles, the heat transfer decreases as the volume fraction of nanomagnetic particles increases. Sheikholeslami et al.[25] studied the free convection problem of magnetic fluid in the cavity in the presence of external magnetic field. The results show that as the volume fraction of magnetic fluid increases, the thickness of the boundary layer becomes larger and the Nusselt number decreases. At the same time, the Nusselt number increases with the increase of Rayleigh number and heat source length, and decreases with the increase of particle size. Mojumder [26] simulated the convection heat transfer of magnetic fluid in a C-shaped cavity under a magnetic field. The study found that compared to the base fluid, the addition of nanoparticles with a solid volume fraction of 15% increased the heat transfer rate to 52.65% at a moderate Rayleigh number. However, the presence of a magnetic field can also hinder the movement of the fluid, resulting in reduced convective heat transfer, which is the result of secondary convection of the ferromagnetic fluid toward the permanent magnet. The negative effects of secondary flow can be reduced by increasing the flow rate. Seo et al. [27] numerically studied the thermal physical properties of magnetic fluid in a vertical rectangle. It was concluded that the isothermal cooling region of the magnetic fluid in the vertical rectangle increases with the increase in the volume fraction of magnetic nanoparticles and the magnetic field strength. This is due to the increase in cooling rate as the magnetic body force increases. Affected by the combined effects of magnetite's heat conduction and magnetic body force, the volume fraction of magnetite nanoparticles increases and the average Nusselt number increases under all magnetic field strengths. Szabo [28] simulated the natural convection in the magnetic fluid square cavity under the influence of permanent magnets. By investigating the extent to which a set of permanent magnets at different distances affects heat transfer, it was found that the intensity of heat transfer almost doubles when the magnets are very close to the fluid, but gradually decreases as the distance increases. Therefore, fluid flow can be actively controlled by adjusting the distance between the permanent magnet and the cavity, thereby reducing or enhancing convection. Selimefendigil et al. [29] simulated the natural convection phenomenon of magnetic fluid in a trapezoidal shell. It was found that as the Rayleigh number and tilt angle increase, the heat transfer increases. External magnetic field parameters (strength and position) can be used to control heat transfer and fluid flow within the trapezoidal cavity. Rahman [30] numerically studied the natural convection heat transfer problem in an equilateral triangular shell filled with water-based and kerosene-based magnetic fluids. The results show that the magnetic field increment reduces the heat transfer rate, and when the magnetic field tilt angle increases, the heat transfer rate increases. In the presence of a magnetic field, there is a strong interaction between cobalt particles and kerosene, which can be used in related projects in the future to enhance the heat transfer effect.

In summary, the simulation study of natural convection of magnetic fluid is consistent with the experimental results. The heat transfer process of natural convection of magnetic fluid can be controlled by applying a magnetic field, thereby reducing or enhancing the convective heat transfer. There are a wide range of factors that affect the natural convection heat transfer of magnetic fluids. Parameters such as nanoparticle type, particle volume fraction, particle size, heat exchanger geometry, Rayleigh number, magnetic field source strength and direction, etc. can all affect natural convection heat transfer. Therefore, so far Unable to conduct systematic research. In order to obtain a more mature magnetic fluid heat transfer theory, parameter influence research based on optimization algorithms should be considered in the future.

## 3 CONCLUSION

At this stage, there is less research on the natural convection heat transfer of magnetic fluids, and more research on the forced convection heat transfer. The results of natural convection heat transfer experiments and simulations show that the natural convection heat transfer process can be controlled using magnetic fluid under an applied magnetic field. By changing the strength and direction of the magnetic field, convective heat transfer can be reduced or enhanced. The natural convection of magnetic fluid has a wide range of influencing factors. In the future, research based on optimization algorithms should be further strengthened to obtain a more mature magnetic fluid heat transfer theory. The research results of forced convection heat transfer show that compared with no magnetic field effect, an external magnetic field can significantly improve the heat transfer of magnetic fluid; compared with a constant magnetic field, the effect of alternating magnetic field on improving convection heat transfer is more significant.

Magnetic fluid has broad prospects in enhancing heat transfer. However, the development of this field is still subject to many challenges, which are summarized as follows: ① The stability, heat transfer mechanism and preparation method of magnetic nanofluid in the presence of magnetic field and gravity field have a great impact on its thermal physical properties; ② It is necessary to solve and explore the flow heat transfer process accompanied by energy input in the alternating magnetic field. Magnetic nanoparticles may generate vortices under the action of the magnetic field, causing the magnetic fluid heat transfer to be significantly affected; ③ The use of magnetic fluid and external magnetic field can control Convection heat transfer process, but precise control is currently difficult to achieve. Research in this area should be strengthened to promote magnetic fluids to application fields such as precision micro heat exchange equipment.

## COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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