Proceedings of the 12th International Conference on Heat Transfer and Fluid Flow (HTFF 2025)
Paris, France - August, 2025
Paper No. HTFF 149
DOI: 10.11159/htff25.149

The Influence of Magnetic Particle Fluid Flow Field Control on Droplet Evaporation

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Abstract

This study investigates the evaporation behavior of deionized water droplets containing micron-sized Fe_2O_3 magnetic particles, focusing on the effects of externally applied magnetic field strength through an active intervention approach. Magnetic fluid droplets were deposited onto a copper pillar surface under various temperature conditions, and their magnetization states were controlled using an electromagnetic rod to apply external magnetic fields. The study involved recording droplet temperature changes, calculating heat flux, and measuring variations in droplet volume and contact angle. In addition, Particle Image Velocimetry (PIV) was employed to analyze the influence of the magnetic field on the flow field, allowing a comparison of evaporation behavior under different magnetic field strengths. The results indicate that under a moderate concentration of magnetic particles and consistent temperature conditions, the droplet evaporation time significantly decreased with increasing magnetic field strength, with this trend becoming more pronounced at higher temperatures. Notably, at 120°C, the applied magnetic field induced rapid expansion and contraction of bubbles inside the droplet, further accelerating the evaporation process. These findings demonstrate that magnetic field strength has a significant effect on droplet evaporation dynamics. The phenomenon reveals the potential applications of magnetic field modulation in heat transfer and fluid dynamics, warranting further exploration and optimization.

***Keywords**: Active intervention, Magnetic particle fluid, Evaporation, Ferrofluid, Heat transfer*

Introduction

The droplet evaporation phenomenon [1] is not only common in daily life, but also in engineering fields such as DNA extraction [2], medical diagnosis [3-5], droplet cooling [6-8] and inkjet [9-10]. Among common the evaporation behaviors on low superheat surfaces, the "Coffee ring effect" and the "Marangoni effect" have attracted widespread attention. These phenomena are influenced by surface properties such as roughness, thermal conductivity and wettability. Evaporative heat transfer on modified surfaces can have a significant impact on heat transfer by changing surface properties. Many studies have shown that surface modification techniques, such as silica coatings, can improve surface wettability and heat transfer mechanisms. For example, Hsu et al. [11] found that graphene coating significantly enhanced the thermal conductivity of copper surfaces. Studies on evaporation heat transfer on heterogeneous annular surfaces show that surface treatment has a significant impact on the evaporation rate and heat transfer mechanism. For example, Hsu[12] and Cheng[13] found that droplets on a non-uniform laser-irradiated surface evaporate faster than droplets on a uniform surface due to increased bubble nucleation sites caused by surface pores, thus accelerating evaporation process. These studies are of great significance for understanding and enhancing the heat transfer mechanism of droplet evaporation.

In recent years, external force fields such as electrowetting of dielectrics (EWOD) have been used to effectively change the surface properties of droplets and accelerate the heat conduction process during evaporation. Studies have shown that changing the contact angle by adjusting the voltage can not only control the transition of droplets on a smooth surface from a hydrophilic to a hydrophobic state, but can also significantly affect the heat transfer rate. For example, Armstrong[14] demonstrated that EWOD can achieve such control on specific surfaces such as SOCAL (Smooth Totally Hydrophobic Covalently Linked Liquid) and SLIP (Smooth Liquid Infused Porous). Furthermore, the effect of surface wettability conditions (e.g., hydrophilic and superhydrophobic surfaces) on droplet shape and heat transfer efficiency was shown using electric field methods. For example, Gibbons[15] Studies have shown that applying an electric field to superhydrophobic surfaces can significantly increase heat flux, while having relatively little effect on hydrophilic surfaces.

Based on these findings, we aim to further investigate the influence of magnetism on evaporative heat transfer, specifically how the orientation of magnetic particles affects droplet evaporation and heat transfer behavior. The research of John[16] explored the thermal conductivity of ferrofluid by adjusting the magnetic field strength, and found that the thermal conductivity increased with the increase of magnetic field strength and Fe_3O_4 concentration. At the same time, Haitao[17] confirmed that Fe_3O_4 nanofluids exhibit higher thermal conductivity at the same concentration, which is attributed to the unique aggregation and arrangement of nanoparticles. These findings highlight the critical role of magnetic fields and nanoparticle concentration in improving heat transfer and droplet evaporation techniques. For example, Ali[18] At constant heat flux, the use of nanofluids and magnetic fields reduced system start-up time by 37% and 30%, respectively, compared to distilled water. In addition, the initial fluctuation temperatures were reduced by 24% and 32% respectively. Du[19] The pool boiling performance and mechanism of Fe_3O_4 nanofluids were studied. The results show that the critical heat flux (CHF) of 0.001 vol% nanofluid is increased by up to 47.90% compared with deionized water. During the boiling process of nanofluids, the CHF and heat transfer coefficient (HTC) of the nanoparticle deposition surface increased by 52.39% and 56.19%, respectively.

The experimental setup of this study was inspired by the work of Cheng[20] and Chen[21] as shown in Fig.1., using a high-speed camera to record the droplet evaporation process at a rate of 50 frames per second. In the experiment, a ceramic heating plate was used to heat a copper rod with a diameter of 3mm to 90/95/110/115/120℃, and was fixed between two electromagnets, and then the electromagnet was connected. The power supply generates magnetic force and is fixed on the aluminum block base and aluminum bar support. The concentration of the magnetic aqueous solution used in this study was 0.05 wt% (20 ml deionized water mixed with 0.01 g magnetic particles). Sonicate to ensure homogeneous mixing and use a syringe with a 1.8 mm needle diameter to distribute the solution onto the surface of the copper rod. This study focuses on the effects of magnetic field strengths from 8V (330 Gs), 10V (430 Gs), 12V (530 Gs), 14V (630 Gs) to 16V (730 Gs) on the droplet evaporation behavior. All data were obtained from five experiments to achieve repeatability.

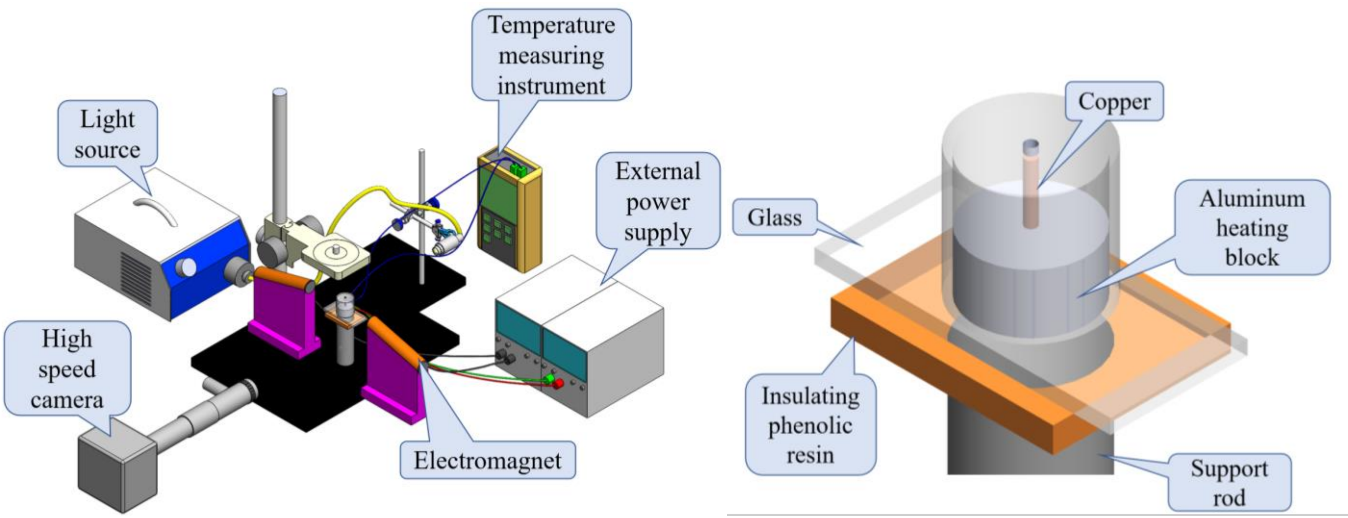

Fig.1. Experimental setup (computer, temperature measuring instrument, power supply, high-speed camera, lamp, syringe pump, needle, copper rod, aluminum block, bakelite, glass, electromagnet).

Result

In order to analyze the heat transfer intensity of the copper surface and its magnetic droplets, when the magnetic droplets are deposited on the heated copper surface, the temperature measurement results on the copper rod will produce a temperature difference. Based on the study of heat transfer by PRN et al. [20], we use Fourier's heat conduction law to calculate the heat flux:

$$q_{eva}=-k\frac{dT(x)}{dx}\ldots\ldots(1)$$

$$\frac{dT}{dx}=\frac{T_2-T_1}{\Delta x}\ldots\ldots(2)$$

In Equations (1) and (2), q_{eva} represents the rate of heat transfer per unit area per unit time, k is the thermal conductivity of copper, $\frac{dT}{dx}$ is the temperature gradient along the direction of heat flow, T_1 is the temperature at the first point, T_2 is the temperature at the second point, and Δx is the distance between the two points.

In the experiment, we measured the variation of heat flux under different temperatures (90°C, 95°C, 110°C, 115°C, and 120°C) and different magnetic field intensities (8V, 10V, 12V, and 14V). From the heat flux graphs as shown in Fig.2. at each temperature, we observed that at the beginning of the experiment, the heat flux remained stable at zero, indicating that our experiment was conducted under steady-state conditions. Subsequently, as the liquid droplet contacted the copper surface, the heat flux value peaked due to the intense heat transfer occurring when the cold droplet made contact with the hot surface. Following this, the droplet began evaporating on the copper surface, causing the heat flux curve to exhibit a gradual and stable decline. As evaporation neared completion and the liquid volume became minimal, the process transitioned into a thin-film evaporation phase, leading to a sudden rise in the heat flux curve. Finally, after complete evaporation, the curve returned to zero. Throughout the entire process, we observed some distinct trends with increasing magnetic field intensity.Under different magnetic field intensities, the peak heat flux increased with stronger magnetic fields. As shown in Fig. 2(a), at 90°C, the peak heat flux was approximately 100 kW/m² without a magnetic field, whereas it increased to about 120 kW/m² under a 14V magnetic field. The effect was even more pronounced at higher temperatures and stronger magnetic fields. As shown in Fig. 2(e), at 120°C, the peak heat flux was around 350 kW/m² without a magnetic field, but it further increased to approximately 400 kW/m² under a 14V magnetic field.

The results derived from the heat flux graphs indicate that as both temperature and magnetic field strength increase, the efficiency of heat transfer significantly improves. This effect is especially evident at higher temperatures, where strong magnetic fields enhance both the peak heat flux and the steady-state heat flux. Additionally, during the evaporation process, the steady-state heat flux also increased with stronger magnetic fields, suggesting that a strong magnetic field may enhance heat transfer efficiency in the droplet evaporation process. The variation in heat flux during the evaporation process further indicates that with increasing magnetic field intensity, the time required for complete droplet evaporation decreases, reflecting the significant influence of the magnetic field on the evaporation process. We will next use imaging and other data analysis to explain why the strong magnetic field results in a higher heat flux.

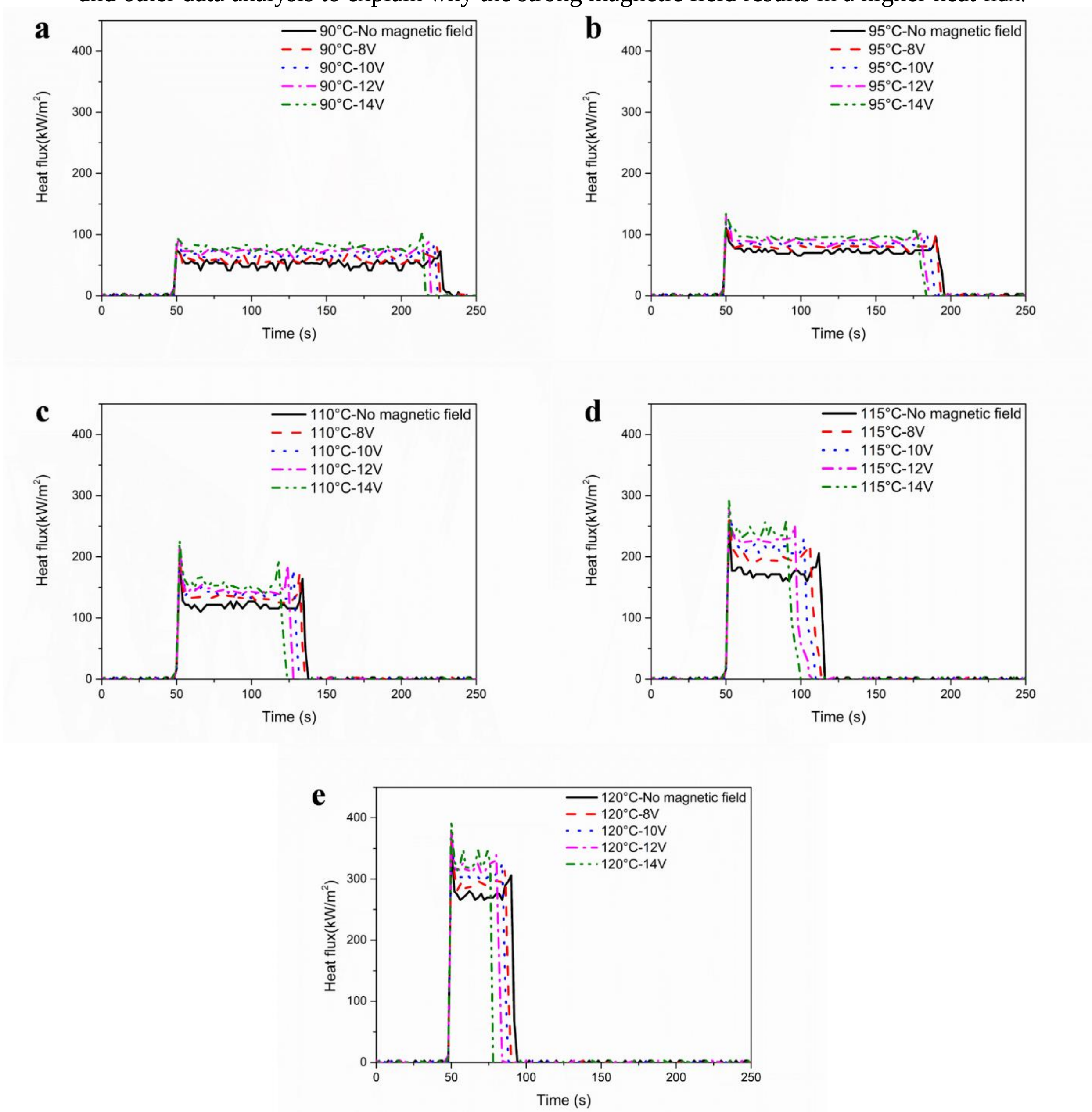

Fig.2. The heat flux curves at different temperatures and magnetic field strengths:(a) 90°C heat flux graph(b) 95°C heat flux graph(c) 110°C heat flux graph(d) 115°C heat flux graph(e) 120°C heat flux graph.(The black solid line represents the condition without a magnetic field.The red dashed line represents the magnetic field at 8V.The blue short-dashed line represents the magnetic field at 10V.The pink dotted-dashed line represents the magnetic field at 12V.The green short-dashed line represents the magnetic field at 14V.)

Conclusion

This study on droplet evaporation investigates the influence of external magnetic field strength through active intervention. The applied magnetic field strengths in this study were controlled at 0V, 8V, 10V, 12V, and 14V. At a relatively low temperature of 90°C, the maximum heat flux of droplets evaporating without magnetic field influence was 100 (kW/m^2), whereas droplets under strong magnetic field influence reached a maximum heat flux of 120 (kW/m²), representing an increase of 20 (kW/m²) in heat transfer compared to the non-magnetic condition. At a higher temperature of 120°C, the maximum heat flux of droplets evaporating without a magnetic field was 250 (kW/m²), while those exposed to a strong magnetic field exhibited a maximum heat flux of 300 (kW/m²), showing an increase of 50 (kW/m²) in heat transfer. Additionally, flow field velocity analysis revealed that as the magnetic field strength increased, the central velocity of the flow field also significantly increased. This study found that at the same temperature, as the magnetic field strength to which the magnetic droplets are subjected increases, the evaporation time of the droplets gradually decreases, and this effect becomes more obvious at higher temperatures.

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