CHF Enhancement by γ-Fe2O3 Nanofluids with Pool Boiling condition on a Downward Facing Plane

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Keywords: pool boiling, cooling electronic equipment, nanofluids, γ-Fe2O3

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CHF Enhancement by $\gamma$-Fe$_2$O$_3$ Nanofluids with Pool Boiling condition on a Downward Facing Plane.

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CHF Enhancement by $\gamma$-Fe$_2$O$_3$ Nanofluids with Pool Boiling condition on a Downward Facing Plane

Abstract

Nanofluids have been widely used in many engineering fields because of their excellent properties, and can be effectively used for cooling electronic equipment and improving energy efficiency. In this study, the heat transfer performance of $\gamma$-Fe$_2$O$_3$ nanofluid was investigated. The particle size used in the experiment is about 20 nm, it can be found by X-ray diffraction (XRD) that it is consistent with the characteristic peak and no other impurities. Nanofluids with different concentrations were configured through a two-step method. Since the $\gamma$-Fe$_2$O$_3$ nanoparticle are not easily dispersed, the ultrasonic time is relatively long. After a series of experiments and data processing, we can see that nanofluids have the best heat transfer performance at 0.07 g/L. Compared to reverse osmosis (R·O) water case, the enhancement of critical heat flux (CHF) is about 34.09 %, and the heat transfer coefficient enhancement is about 49.32 %. The movement of bubbles during the experiment is recorded and analyzed. Compared with R·O water case, the bubbles are larger and fewer in the nanofluid case, and what’s more, the bubble movement is relatively intense. The heating surface was characterized after the experiment, and it was found that the wettability of the heating surface was changed, and the roughness of the heating surface decreased. SEM shows that the deposition of nanoparticles on the heating surface is the main cause of CHF enhancement. When the concentration is 0.08 g/L, CHF decreases, mainly because the excessive deposition of nanoparticles increases the thermal resistance of the heating surface and leads to the deterioration of the heat transfer.

Keywords pool boiling · cooling electronic equipment · nanofluids · $\gamma$-Fe$_2$O$_3$
1. Introduction

Electronic device cooling is one of the major challenges of the new generation of electronic packaging technology. The power consumption of electronic devices, chip power consumption and heat flux have been steadily increasing, hence the need for improved cooling methods. The determination of heat transfer fluid suitable for heat dissipation is of great significance to the thermal management of electronic equipment.

It is well known that the high power consumption and failure of electronic chips are due to the sharp increase in heat flow per unit area caused by the reduction of the size of electronic components, which causes thermal problems and reduces the performance and reliability of the chip. These problems are among the challenging tasks in the development of next-generation integrated circuits, microprocessors, and other compact integrated storage devices. Today, different types of heat exchangers and cooling techniques are used in electronic cooling. There are many methods of electron cooling, such as pool boiling (Arik and Bar-Cohen 2010), jet impact cooling (Nishino et al. 1996; Chung et al. 2002) microchannel two-phase flow (Lin et al. 2002; Honda and Wei 2004), spray cooling (Lin and Ponnappan 2003), and heat pipe cooling (Zhao and Avedisian 1997; Wang and Vafai 2000; Kim et al. 2003). Many studies have shown that the existing cooling technology and traditional methods are still facing the problem of integrated circuit heat dissipation.

Due to the rapid development of modern technology, the current electronic system will generate a lot of heat, which will deteriorate the performance of the device and reduce the reliability (Saidur et al. 2011). In various electronic cooling systems, the most commonly used coolants: air, water, ethylene glycol, etc., can not meet the heat dissipation requirements of high heat flux. As one of the most effective heat dissipation methods, boiling heat transfer has a wide range of applications in industrial production and daily life, but with the development of science and technology, there are higher requirements for heat dissipation methods. In the process of heat transfer, the most important thing is that the heat flux density
of the heating surface cannot exceed critical heat flux (CHF) (Liang and Mudawar 2018a). Researchers are working hard to find a better way to improve heat transfer performance. Electronic components can be cooled by airflow, but airflow has a lower cooling potential, and liquids with better thermal capacity have a higher cooling potential than gases. Advances in the thermophysical behavior of fluids have improved the cooling effect, allowing the use of smaller electronic systems. Nanofluids may be suitable for this goal. Among them, the preparation of nanofluids by adding nanoparticles into the base fluid has attracted the attention of many researchers. Through a series of experiments (Liang and Mudawar 2018b), it was found that the addition of nanoparticles can indeed change the heat transfer performance.

Nanofluid refers to a colloidal liquid prepared by uniform mixing of nanoparticles between 1—100 nm in a base liquid (Choi 2009). Compared with the pure liquid, the thermal conductivity and viscosity of the prepared fluid changed significantly. The particle size of the three nanoparticles are 13 nm, 12 nm, and 27 nm, respectively. You et al. (You et al. 2003) found that the heat transfer performance of 0.005 g/L Al₂O₃ nanofluids was 200% higher than that of pure water, but the boiling heat transfer coefficient was almost no difference. After continuing research, it was found that when the heating surface was changed from top to bottom, the effect of CHF enhancement was more significant. By comparison, it was also found that the size of the bubbles in the nanofluid and the frequency of bubble increases were significantly reduced. In addition to the enhancement of CHF by nanofluids, some researchers have confirmed that nanofluids can also enhance HTC. Wen et al. (Wen and Ding 2005) found that Al₂O₃ nanofluids can significantly enhance HTC, with an enhancement of about 40% when the mass concentration is 1.25%, and the size of the nanoparticles in the experiments is about 10-50 nm. The reason for the enhancement is believed to be mainly related to the properties of the nanofluid and the boiling surface. Subsequently, they measured the HTC enhancement of about 50% in TiO₂ nanofluids at a volume concentration of 0.7% under the same conditions. Ali et al. (Ali et al. 2017) found that boiling heat transfer experiments were performed on distilled water and two concentrations of TiO₂ nanofluids using a circular copper plate as a heating device. Compared to distilled water case, the HTC enhancement of TiO₂ nanofluids with a mass concentration of 15% and 12% is 38% and 24%, respectively. Although many researchers have found that nanofluids can enhance the heat transfer performance, some researchers have found that nanofluids can also cause the deterioration of heat transfer performance. Das et al. (Das et al. 2003) observed that in the case of water-based Al₂O₃ nanofluid as the experiment fluid, the HTC decreased continuously with increasing concentration, especially at high heat flux. They believe
this is due to the reduced roughness of the heating surface and they also further quantified this feature.

It can be seen that although researchers have conducted a lot of research, it is not enough to fully summarize the enhanced heat transfer performance of nanofluids, and more researches and discussions are needed to explore the mechanism. Because iron oxide is relatively easy to produce and the cost is relatively cheap. After reviewing the literature, it can be found that there are few studies on it. If its performance is fully studied, the future application prospects should be more and more extensive, so in this paper, different concentrations of $\gamma$-Fe$_2$O$_3$ nanofluids were selected to investigate their heat transfer performance in an experimental setup with a downward heating surface.

2 Experimental setup and method

2.1 Nanofluids preparation and materials

The preparation methods of nanofluids are divided into one-step method and two-step method. In this experiment, the two-step method is used to prepare nanofluids, that is, to obtain nanoparticles first, and then to disperse the nanoparticles evenly in the base liquid through some instruments and equipment. Because the addition of additives will have an effect on the heat transfer properties of nanofluids, and we want to discuss the heat transfer properties of $\gamma$-Fe$_2$O$_3$ only, no additives are added in this experiment. The preparation of nanofluids mainly adopts a two-step method. First, stir with a stirrer at a speed of 1800 per minute for 30 minutes. However, due to the characteristic particle of $\gamma$-Fe$_2$O$_3$, which is relatively small and heavy, we oscillated in the ultrasonic oscillator for a long time, about 120 min. Assuming that the power of the package chip is very high, the heat flux is very high under a certain unit area, so the experimental method we use is designed for the heat dissipation of the small-size package.

2.2 Experimental setup

Pool boiling experiment is the most mature and common type of boiling experiment in heat transfer. During the boiling process, due to the limitation of boiling space and pressure, vapor and liquid are mixed together to form a gas-liquid two phase mixture. In this experiment, in order to observe the generation and movement of bubbles on the heating surface, a visual experimental platform was built, just as shown in Fig. 1. The platform mainly includes a special heating block, a transparent water tank, two T-type thermocouples, two K-type thermocouples, a data recorder system, a power supply, and two 4K cameras.

The special heating block used in the experiment is the core part of our entire experimental system, which is improved on the basis of the design of Heish(Hsieh et al. 2015b, a), and its schematic diagram is shown in Fig. 2. To make it easier to observe the heating surface during the experiment, two glass
Sheets were placed on both sides of the heating area. The distance between the two pieces of glass is 10 mm, and a K-type thermocouple was placed in the center of the heating area to measure the temperature change of the heating surface.

2.3 Experimental method

The heat flux in the experiment is mainly obtained through the basic equation of heat transfer—Fourier’s law, as shown in Eq. (1), in the formula, $q''$ is the heat flux, which unit is $W/m^2$, $\lambda$ is the thermal conductivity of the internal trapezoidal structure of the heating block, which unit is $W/m \cdot K$, $A$ is the area of the heating surface, since the heating block is made of SS304 steel, and its thermal conductivity $\lambda$ varies with the temperature (Ho and Chu, 1977), and the corresponding relationship is shown in Table 1. $T_1$ and $T_0$ are the internal and external temperatures of the heating block measured by the thermocouples, respectively. $\Delta x$ is the distance between the two thermocouples. By the equation above, the heat flux of the heating block can be calculated.

$$q'' = \lambda A \frac{T_I - T_O}{\Delta x}$$  Eq. (1)

The heat transfer coefficient of nanofluid is mainly obtained from Newton’s cooling formula. In Eq. (2), $T_o$ is the surface temperature of the heating block, and $T_a$ is the average temperature of nanofluid, units are in °C, obtained from two T-type thermocouples in the water tank.

$$q'' = h(T_o - T_a)$$  Eq. (2)

2.4 Uncertainty and reliability analysis

In this experiment, the error of direct measurement mainly includes three aspects: the error of the data recorder system, the measurement error of the thermocouple, and the error of the ruler measurement. The error of indirect measurement is mainly calculated from the errors of multiple direct measurements. If the directly measured data value is $H$, which is a function of the directly measured values $x_1, x_2, x_3,\ldots,x_n$, that is $H(x) = f(x_1, x_2, x_3,\ldots,x_n)$, since the measurement error of each parameter were listed in the Table 2, the uncertainty of the indirectly measured value can be calculated by the formula given by Moffat (Moffat, 1988):

$$\Delta H = \sqrt{ \left( \frac{\partial H}{\partial x_1} \Delta x_1 \right)^2 + \left( \frac{\partial H}{\partial x_2} \Delta x_2 \right)^2 + \left( \frac{\partial H}{\partial x_3} \Delta x_3 \right)^2 + \cdots + \left( \frac{\partial H}{\partial x_n} \Delta x_n \right)^2 }$$  (2-3)

The uncertainties of temperature (T), distance (D), area (A), heat transfer coefficient (h), heat flux ($q''$), are calculated respectively, and the uncertainties are 0.410 %, 0.40 %, 0.406 %, 0.770 %, and 0.505 %.

During the experiment, the stability of the experimental system is very important. Therefore, before
the experiment, we carried out the repeated pool boiling experiment on the experimental system in the R·O water case. Before each experiment, the consistency of the experimental environment was strictly guaranteed, and five pool boiling experiments were carried out according to the unified process. After calculation, the heat flux densities when CHF occurs in five experiments are: 387.28 kW/m$^2$, 392.92 kW/m$^2$, 399.84 kW/m$^2$, 405.91 kW/m$^2$, 410.76 kW/m$^2$. The average value of heat flux is 399.34 kW/m$^2$, and the processing results are shown in Fig. 3. The relative errors of these five experiments are calculated by formula Eq. (3) as 3.11 %, 1.63 %, 0.13 %, 1.65, 2.86 %, the relative error is less than 4 %, indicating that our pool boiling experiment system has good repeatability and high reliability, and can be used for experiments.

\[ E_r = \frac{|q_{CHF} - q_{CHF}|}{q_{CHF}} \times 100\% \quad \text{Eq.(3)} \]

3. Results and discussion

3.1 Characterization of nanoparticles

Since the heat transfer properties of nanofluids and not the preparation of nanoparticles is mainly discussed in this paper, the nanoparticles are purchased. Before preparing the nanofluid, we characterized the nanoparticles first by XRD and SEM. Fig. 4 is the XRD diffraction spectrum of $\gamma$-Fe$_2$O$_3$ nanoparticles (PDF#04-0755), and the characteristic peaks from left to right are 30.24°, 35.63°, 43.28°, 53.89°, 57.27°, 62.92°, 74.68°, corresponding to (2 2 0), (3 1 1), (4 0 0), (4 2 2), (5 1 1), (4 4 0), crystal planes. No other characteristic peaks are found in the figure. It can be seen that there are no other impurities in the nanoparticles. And we can see from the SEM images in Fig. 5 that the $\gamma$-Fe$_2$O$_3$ nanoparticles are spherical and uniform in size. The size is about 20 nm, which meets the requirements of the experiment.

In this experiment, a total of 6 different concentrations of $\gamma$-Fe$_2$O$_3$ nanofluids were prepared, which were 0.01 g/L, 0.02 g/L, 0.04 g/L, 0.06 g/L, 0.07 g/L and 0.08 g/L, respectively. As can be seen from the Fig. 6, as the concentration increases, the nanofluid also gradually becomes cloudy. The stability of nanofluids is measured by ultraviolet spectrophotometer (UV-Vis), the absorbance of nanofluids changes over time. Fig. 7 is the absorption spectrum of $\gamma$-Fe$_2$O$_3$ nanofluids, the highest absorption peak is around 372 nm, and there is also a second highest absorption peak at 255 nm. Although after 120 min of sonication, the absorbance of the $\gamma$-Fe$_2$O$_3$ nanofluid changed rapidly with time, and dropped from 0.69 to 0.61 in 2 hours. It has higher energy and settles after colliding with other nearby nanoparticles during continuous motion. Therefore, the absorbance of the nanofluid will decrease faster after the preparation.
is completed, but since we start the experiment after the preparation is completed and cooled to below 30°C, and the experiment will end within two hours, so during this process the deposition of γ-Fe₂O₃ nanoparticles has little effect on the experiment.

### 3.2 Preparation and characterization of nanofluids

Because the addition of additives will have an effect on the heat transfer properties of nanofluids, and we want to discuss the heat transfer properties of γ-Fe₂O₃ only, no additives are added in this experiment. The preparation of nanofluids mainly adopts a two-step method. First, stir with a stirrer at a speed of 1800 per minute for 30 minutes. However, due to the characteristic particle of γ-Fe₂O₃, which is relatively small and heavy, we oscillated in the ultrasonic oscillator for a long time, about 120 min.

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### 3.3 Boiling characteristics of γ-Fe₂O₃ nanofluids

During the experiment, the two cameras at the bottom and the side recorded the experimental phenomenon on the surface of the heating block during the experiment, and the thermocouple also recorded the temperature change of the heating surface with time. Similar to the typical liner heating pool boiling experiment, the experimental process mainly includes three stages (Liang and Mudawar 2017a, b): natural convection zone, nucleate boiling zone (including the isolated bubble zone in the early stage and the film boiling region. However, due to the downward heating surface, when the bubbles are formed, they will accumulate on the heating surface due to the dual action of buoyancy and gravity and form a film earlier, so the CHF in this experiment is relatively low, and the time of occurrence also earlier, the
three stages of pool boiling last for a shorter period of time.

The $\gamma$-Fe$_2$O$_3$ nanofluid is turbid at high concentration, so the heating surface cannot be observed. In this paper, the bubbles behavior of the heating surface under the case of 0.01 g/L is selected to compare with the R·O water case to find the difference.

Fig. 8 is the images of the temperature of the heating surface changing with time, and the time of the experimental phenomenon in the figure has been marked in the approximate position. It can be seen that in the natural convection stage, after the experiment is carried out for 100 s, the temperature under each case has changed, and the surface temperature is lower under the higher concentration of nanofluid, indicating that the nanofluid promotes heat transfer. In the isolated bubble zone, the heating surface temperature in different concentrations is also different, but all are lower than the R·O water case. The surface temperature stabilizes only when entering the nucleate boiling zone. And it also can be seen that the film formation time is also advanced in all nanofluid cases, we believe that the viscosity of the nanofluid is relatively high, and the bubbles are more likely to be generated. With the increase of the concentration, the duration of the film boiling zone increases gradually. The CHF takes the longest time at 0.08 g/L, about 1090 s, and the CHF takes about 1069 s at 0.07 g/L. In addition, the surface temperature of the heating surface also gradually increased with time, when CHF occurred, the surface temperature of the heating block was about 116 °C under the case of 0.07 g/L, while the R·O water case is 106 °C.

It can be seen from the experimental phenomenon that in the isolated bubble zone, compared with R·O water case (a$_1$), the number of bubbles on the heating surface of the nanofluid case (a$_2$) is relatively small, and the behavior of the bubble is the process of a small amount of bubbles gradually increasing rather than the formation process of small bubbles. And at the beginning of the nucleate boiling zone of the nanofluid case (b$_2$), the bubbles move more frequently, and the process is mainly accompanied by the gradual fusion of small bubbles, while in the R·O water case (a$_2$), it is the growth and rupture process of the bubbles. The reasons for the movement of the bubbles mainly include the heat flow disturbance during the heating process, but also related to the Marangoni effect, the mass flow caused by the difference of the nanofluid concentration in the tiny area of the heating surface, which drives the movement of the bubbles, in addition, it is also related to Brownian motion. But this phenomenon is not observable in the R·O water case. (c$_1$) and (c$_2$) are the phenomenon photo of R·O water case and nanofluid case when they are about to enter the film boiling zone. At this time, compared with R·O water case, bubbles in nanofluid case move more intensely, and there are relatively few small bubbles around.
Besides, the nanofluid case can greatly prolong the film boiling time. The time of film boiling increases with the increase of the concentration in the experiment, and the thickness of the film is also thicker and thicker. As shown in the figure, in the R·O water case (d₁), the film thickness is 5.34 mm when CHF occurs and in the 0.01 g/L γ-Fe₂O₃ case (d₂), the film thickness is 6.10 mm, we can infer that the film thickness of the heating surface increases with increasing concentration and time.

After processing the data, the relationship between the heat transfer coefficient and heat flux of the γ-Fe₂O₃ nanofluid is obtained as shown in Fig. 9. It can be seen that in the low heat flux zone of 100—200 kW/m², the heat transfer coefficients of all nanofluid cases are much higher than that of R·O water case. This is mainly because the ultrasonic time is very long, so the nanoparticles have higher energy, the movement is more violent, and the collisions between the nanoparticles are also more frequent. Part of the heat is also consumed during the movement of the nanoparticles, so it has a higher heat transfer coefficient. With the increase of the heat flux, there is a plateau region in the curve, which corresponds to the nucleate boiling zone in the process of pool boiling. Then the heat transfer coefficient increases linearly with the increase of heat flux. The heat transfer performance of γ-Fe₂O₃ nanofluid is the best under the case of 0.07 g/L, the heat flux when CHF occurs is 536.16 kW/m², and the heat transfer coefficient is 6.89 kW/m²·K. The heat transfer performance decreased a little when the concentration is 0.08 g/L, the heat flux is 515.51 kW/m², and the heat transfer coefficient is 6.45 kW/m²·K.

Fig. 10 shows the relationship between superheat ΔT and heat flux density q". It can be seen that in the natural convection zone with low superheat, the heat flux is different under the same superheat, which corresponds to the enhancement of heat transfer efficiency caused by the high energy of nanofluid. Then with the increase of superheat, the heat flux under the nanofluid case has exceeded the R·O water case. In the nucleate boiling zone, the heat flux of the same superheat at each concentration has a certain cross. However, after entering the film boiling zone, the superheat of each case is different when CHF occurs, but they are all smaller than the R·O water case, mainly due to the long ultrasonic time during the configuration process of the γ-Fe₂O₃ nanofluid. This results in a higher nanofluid temperature and therefore lower superheat.

3.4 Characterization of heating surface

To explore the heat transfer mechanism of nanofluids, the characterization and analysis of contact angle, roughness, SEM and EDS were carried out on the heating surface under the case of γ-Fe₂O₃ after the experiment.
Contact angle is a common parameter used to characterize surface wettability. When the water droplet angle is less than 90°, the smaller the angle, the better the wettability and hydrophilicity. In RO water case, the wettability of the heating surface is 90°. Fig. 11 shows the droplet angle on the heating surface of all γ-Fe$_2$O$_3$ nanofluid cases. It can be seen that with the increase of the nanofluid concentration, the water droplet angle of the heating surface gradually decreases, and the wettability of the surface is also getting better and better. When the concentration is 0.07 g/L, the water droplet angle is 62.906°, and when the concentration is 0.08 g/L, the water droplet angle is 55.547°. That is, as the concentration increases, the wettability of the nanofluid gradually decreases.

Fig. 12 shows the SEM image of the heating surface under the RO water case and the SEM and EDS images of the heating block surface under the 0.07 g/L γ-Fe$_2$O$_3$ nanofluid case. It can be seen that there is deposition of nanoparticles on the heating surface. The particle size of γ-Fe$_2$O$_3$ nanoparticles is relatively small (about 20 nm), so the nanoparticles are mainly deposited in the gaps between the grains on the heating surface, and there is also a small amount of deposition on the surface of the grains. However, in the RO water case, there is no deposition of nanoparticles on the heating surface, and the wettability does not change. It can be seen that this is the main factor for the decrease of the wettability of the heated surface.

Table 3 shows the roughness of the heating surface changes before and after the experiment. Some researchers have observed that the roughness of the heating surface has a strong relationship with the CHF (Kim et al. 2016). In this experiment, it can be seen that under the RO water case, the roughness hardly changes, while in the nanofluid cases, the roughness of the heating surface all decreased, which is related to the deposition of the nanoparticle. Nanoparticles fill the gap on the surface of the heating block, and then reduce the surface roughness. and the roughness decreases more at high concentrations. Due to the limitation of experimental equipment, we cannot find any relationship yet, the influence of roughness needs to be further explored in a further experiment.

3.5 Mechanisms of nanofluids affecting boiling heat transfer

In the process of boiling heat transfer, there are many factors that affect heat transfer, and each factor will also have mutual influence and effect. Combining the experimental phenomena and characterizations in this experiment and others research, we believe that the heat transfer performance of nanofluids is the result of a combination of factors. Such as Brownian motion, Marangoni effect, thermophoresis, etc. In addition, through experimental characterization and previous experimental studies (Zhou et al., 2021,
(Zhang et al., 2022), it can be found that the effect of nanoparticle deposition on the heating surface is the main factor for the enhancement of CHF under nanofluid cases. Due to the deposition of nanoparticles, a porous layer is formed on the heating surface. These porous layers are mainly at and near the gaps between the grains of the heating surface. The deposited nanoparticles not only enhanced the wettability of the surface, but also increased the specific surface area of the heating surface, which further improved the heat transfer performance.

However, it can be seen from the experiment that the heat transfer performance of the nanofluid has not increased but decreased at a higher concentration (0.07 g/L). We believe that the reason for this is that the decrease of the heat transfer coefficient at this time is due to the excessive deposition of nanoparticles, which increases the resistance parameters and thermal resistance (Huang et al. 2011) of the heating surface, resulting in the deterioration of heat transfer. Furthermore, due to the excessive deposition of nanoparticles, the number of active nucleation sites is reduced, forming an insulating porous layer. When a certain limit is reached, heat transfer deterioration occurs earlier.

4. Conclusion

In this experiment, the heat transfer performance of $\gamma$-$\text{Fe}_2\text{O}_3$ nanofluids with different concentration in pool boiling was studied. After that, the surface was characterized and analyzed, and the following conclusions were obtained:

1. In the pool boiling experiment, $\gamma$-$\text{Fe}_2\text{O}_3$ nanofluid enhanced CHF and heat transfer coefficient, and both of them increased with the increase of concentration. The maximum CHF enhancement was about 34.09% and the maximum heat transfer coefficient enhancement was 49.32%.

2. In the nanofluid case, the bubble movement is also more intense due to the action of nanoparticles, and the heat transfer performance in each stage of pool boiling is better than that in R·O water case.

3. In all nanofluid cases, the time of entering the film boiling zone is earlier than that in R·O water case, and the time of CHF occurrence is prolonged with the increase of nanofluid concentration, the surface temperature is also higher than R·O water case.

4. The deposition of nanoparticles is the main reason for CHF enhancement, which not only increases the number of vaporization cores and nucleation sites, but also changes the roughness and wettability of heating surface. However, at high nanofluid concentration, due to the excessive deposition of nanoparticles, the surface thermal resistance will increase when a certain limit is reached, leading to
the deterioration of heat transfer.

In summary, compared with RO water, γ-Fe₂O₃ nanofluids has better heat transfer performance in pool boiling experiment. These studies show the potential of nanofluids as good liquid coolants for electronic devices and are expected to be candidate coolants for the next generation of thermal management systems for high-heat dissipating electronic systems. In addition, due to the advantage of simple preparation and economic applicability, γ-Fe₂O₃ nanofluid has higher potential value in heat transfer, and the mechanism of CHF enhancement needs to be extensively studied in the future.

Declaration of Competing Interest

There is no conflict of interest.

Acknowledgement

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Reference


Table 1 Relationship between thermal conductivity and temperature of SS304 steel.

<table>
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<th>$\lambda$ (W/m · K)</th>
<th>Temperature (K)</th>
<th>$\lambda$ (W/m · K)</th>
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<td>Power supply</td>
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### Table 3 Roughness parameters of all cases.

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<tr>
<th>Case</th>
<th>Condition</th>
<th>$R_a$ μm</th>
<th>$R_q$ μm</th>
<th>$R_z$ μm</th>
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<tr>
<td>R·O water</td>
<td>Before</td>
<td>0.117</td>
<td>0.202</td>
<td>1.257</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>0.115</td>
<td>0.205</td>
<td>1.261</td>
</tr>
<tr>
<td>0.01 g/L</td>
<td>Before</td>
<td>0.123</td>
<td>0.183</td>
<td>1.462</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>0.099</td>
<td>0.121</td>
<td>0.859</td>
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<tr>
<td>0.02 g/L</td>
<td>Before</td>
<td>0.124</td>
<td>0.188</td>
<td>1.097</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>0.101</td>
<td>0.170</td>
<td>1.139</td>
</tr>
<tr>
<td>0.04 g/L</td>
<td>Before</td>
<td>0.128</td>
<td>0.256</td>
<td>2.362</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>0.104</td>
<td>0.144</td>
<td>1.252</td>
</tr>
<tr>
<td>0.06 g/L</td>
<td>Before</td>
<td>0.115</td>
<td>0.175</td>
<td>1.138</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>0.083</td>
<td>0.135</td>
<td>1.233</td>
</tr>
<tr>
<td>0.07 g/L</td>
<td>Before</td>
<td>0.117</td>
<td>0.198</td>
<td>1.642</td>
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<td>After</td>
<td>0.081</td>
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<td>0.130</td>
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Fig. 1 (a) Experimental system diagram; (b) Schematic of the experimental system.

Fig. 2 Internal structure diagram of the heating block.
Fig. 3 Pool boiling experiment under R-O water condition.

Fig. 4 XRD patterns of $\gamma$-Fe$_2$O$_3$ nanoparticles.
Fig. 5 SEM images of $\gamma$-Fe$_2$O$_3$ nanoparticles

Fig. 6 Photographs of $\gamma$-Fe$_2$O$_3$ nanofluids with different concentrations
Fig. 7 UV-VIS spectra of $\gamma$-Fe$_2$O$_3$ nanofluids at different time
Fig. 8 The records of surface temperature during boiling process of all cases and the images of experimental phenomenon of heating surface.
Fig. 9 Heat transfer coefficient ($h$) with heat flux ($q''$) at different concentrations

Fig. 10 Heat flux ($q''$) with superheat ($\Delta T$) at different concentrations
Fig. 11 Contact angles of different concentrations.

Fig. 12 SEM images of heating surface: (a) R·O water case; (b) γ-Fe₂O₃ nanofluids case, and (c) EDS images of γ-Fe₂O₃ nanofluids case.