ABSTRACT: Boiling heat transfer intensification is of significant relevance to energy conversion and various cooling processes. This study aimed to enhance the saturated pool boiling of FC-72 (a dielectric liquid) by surface modifications and explore the mechanisms of the enhancement. Specifically, circular and square micro pin fins were fabricated on silicon surfaces by dry etching and then copper nanoparticles were deposited on the micro-pin-fin surfaces by electrostatic deposition. Experimental results indicated that compared with a smooth surface, the micro pin fins increased the heat transfer coefficient and the critical heat flux by more than 200 and 65–83%, respectively, which were further enhanced by the nanoparticles up to 24% and more than 20%, respectively. Correspondingly, the enhancement mechanism was carefully explored by high-speed bubble visualizations, surface wickability measurements, and model analysis. It was quantitatively found that small bubble departure diameters with high bubble departure frequencies promoted high heat transfer coefficients. The wickability, which characterizes the ability of a liquid to rewet a surface, played an important role in determining the critical heat flux, but further analyses indicated that evaporation beneath bubbles was also essential and competition between the wicking and the evaporation finally triggered the critical heat flux.

INTRODUCTION

Currently, we are in the age of digitalization, intelligentization, and automation, which greatly depends on electronics varying from small laptops to large servers and data centers, where electronic cooling is a big issue that affects the efficiency and life span. Therefore, it is important to have a rational cooling scheme. To date, air cooling is still the commonly employed cooling solution in data centers, but the capacity is usually limited by poor thermal properties of air, even with some enhancement strategies, e.g., heat sinks. In addition, miniaturization and integration of electronics result in large increases in the heat load. For example, it is reported that the heat load of a blade server could reach up to 7.5–10.5 kW by 2020, which might be too high to be dissipated rapidly by air cooling. Therefore, an advanced cooling method is desired to meet the heat dissipation demand. Stimulated by this, a supercooling scheme utilizing boiling heat transfer, viz., immersion cooling, is quite competitive because boiling has at least one order of magnitude higher heat transfer coefficients than air-forced convection, and the immersion cooling has been regarded as the next technology for data center cooling. A few attempts have been made to investigate the immersion cooling performance with water and dielectric liquids, e.g., FC-72, HFE-7100, and Novec-649. It has been found that water presents a higher cooling capacity but with a penalty of high surface temperatures that normally surpass the transistor junction temperature (typically 85 and 110 °C in special high-temperature applications). In contrast, dielectric liquids have good chemical compatibility with semiconductor materials and relatively low saturation temperatures, e.g., FC-72 with a saturation temperature of 56 °C under atmospheric pressure, which makes them suitable for electronic cooling. Accordingly, it is essential to investigate the boiling performance of dielectric liquids with respect to their application in electronic cooling.

The boiling performance is characterized by the heat transfer coefficient (HTC) and critical heat flux (CHF). The heat transfer coefficient represents heat transfer capacity, and the critical heat flux denotes a heat flux beyond which the boiling heat transfer will transit from nucleate boiling to transient boiling or film boiling, resulting in a large increase in the surface temperature and a heat transfer deterioration that might cause burnout of electronics. Therefore, it is important to enhance the heat transfer and the critical heat flux in practice. The boiling performance strongly depends on bubble
dynamics, i.e., bubble nucleation, bubble–bubble interactions, and bubble–liquid interactions that can be tuned by active methods, e.g., external electrical field and magnetic field.\textsuperscript{11} Alternatively, the performance can be manipulated via passive methods, e.g., surface modifications\textsuperscript{12} to change surface characteristics, e.g., wettability and roughness. The passive method is more extensively studied as it is energy free and due to emerging surface engineering technologies.

To date, numerous technologies have been implemented to tailor boiling surfaces, generating micro-/nanostructures, e.g., cavities, pores, and irregularities on surfaces. These structures can generally intensify bubble nucleation and liquid rewetting, and thus improve the boiling performance. For example, the sintering technique was used to produce porous coatings, and pool boiling of water,\textsuperscript{13–15} acetone,\textsuperscript{16} and FC-72\textsuperscript{16,17} was examined. The electrochemical (electroplating) deposition was also widely employed to generate microporous coatings on which pool boiling of FC-72,\textsuperscript{20,21} Novec-649,\textsuperscript{22} HFE-7200,\textsuperscript{23} and water\textsuperscript{24–27} was studied. Other coating technologies involve atomic layer deposition,\textsuperscript{28–30} oxidation,\textsuperscript{31,32} chemical vapor deposition,\textsuperscript{30,33–35} electrophoretic deposition,\textsuperscript{36–39} etc. In addition, a wet/dry etching technique was used to fabricate micro pin fins,\textsuperscript{40–44} micro cavities,\textsuperscript{45} and nanowires,\textsuperscript{46–48} while a new emerging laser technique was also attempted to modify the boiling surfaces, obtaining micro pin fins\textsuperscript{49–51} and micro cavities.\textsuperscript{52} Pool boiling of various liquids was experimentally investigated on the surfaces mentioned above, including SES36,\textsuperscript{57} HFE-7200,\textsuperscript{18,39} FC-72,\textsuperscript{41,43,49,50} n-pentane,\textsuperscript{1} and water, and on other surfaces. It was found that the boiling performance was considerably enhanced, but micro/nano-composite structures generally were more favorable than sole micro- or nanostructures concerning the heat transfer coefficient or the critical heat flux.\textsuperscript{30,41,53} In terms of the enhancement mechanisms, heat transfer enhancement was usually attributed to several aspects, e.g., the increase in active nucleation site density, effective bubble dynamics, and enlarged heat transfer area, but the mechanisms of critical heat flux enhancement varied in various studies, e.g., liquid–vapor competition inside structures,\textsuperscript{16} wicking intensification,\textsuperscript{54,40,47,54} and liquid–vapor hydrodynamic instability.\textsuperscript{39}

To the best of the authors’ knowledge, although so much discussion has been presented concerning the boiling enhancement mechanism, it is still not well understood; there is a lack of detailed and quantitative bubble dynamics regulations by surface structures especially for well-wetting liquids and a controversy over the critical heat flux enhancement mechanism. Accordingly, this study aims to fabricate novel enhanced surfaces for boiling, investigate the coupling between bubble dynamics and heat transfer, and explore the possible mechanism of the critical heat flux enhancement.

Specifically, pool boiling heat transfer of FC-72 was experimentally studied on micro-pin-fin surfaces in this study and then the effect of nanoparticles on the boiling performance was revealed. Bubble visualizations at low heat fluxes (<6 W/cm\textsuperscript{2}) were captured by a high-speed camera, from which bubble departure diameter and bubble departure frequency were quantitatively measured, corresponding to the heat transfer performance. Surface wickability was measured and compared, shedding light on the critical heat flux enhancement mechanism. Furthermore, a model-based analysis was conducted considering liquid wicking and liquid evaporation, accounting for a nonmonotonic trend between the wickability and the critical heat flux on the micro-pin-fin surfaces with nanoparticles.

### EXPERIMENTAL SECTION

**Boiling Surface Preparation.** In this study, single-sided polished P-doped silicon surfaces were used as the substrate with a size of 10 mm × 10 mm × 0.5 mm in length, width, and thickness, respectively. Micro pin fins were fabricated on the silicon surfaces by a dry etching technique and the detailed process was described in our previous work.\textsuperscript{17} In this work, one circular-pin-fin surface (CPF-1) and two square-pin-fin surfaces (SPF-1 and SPF-2) were prepared. The circular pin fin has a diameter (d) of 38 μm and a height (h) of 60 μm, while the square pin fin has a width (w) of 30 μm and a height of 60 μm. The CPF-1 and the SPF-1 have the same pitch (p) of 60 μm between two neighboring pin fins, while the SPF-2 has a pitch of 45 μm.

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Figure 1. Images of the test surfaces obtained by scanning electron microscopy (SEM).
To further tailor the boiling performance, copper nanoparticles were deposited on the micro-pin-fins surfaces using an electrostatic deposition method, while 1 h (NP1) and 2 h (NP2) depositions were carried out, obtaining six nanoparticle-coated micro-pin-fins surfaces, viz., CPF-1-NP1, CPF-1-NP2, SPF-1-NP1, SPF-1-NP2, SPF-2-NP1, and SPF-2-NP2 summarized in Table S1 in the Supporting Information. Section S1 in the Supporting Information presents a detailed description of the deposition process, with a schematic diagram of the electrostatic deposition method shown in Figure S1. The nanoparticle has a diameter of 0.5−100 nm, which has a quasi-Gaussian distribution with nanoparticle concentrations, and the peak concentration corresponds to a diameter of around 23 nm, as shown in Figure S2 in the Supporting Information.

All test surfaces were characterized by field emission-scanning electron microscopy (SEM) (Hitachi SU8010), as shown in Figure 1. It is seen that the micro pin fins are patterned with a staggered configuration. The square pins (SPF-1) provide a larger porosity than the circular pin fins (CPF-1), while they have a very similar extended surface area. The large porosity gives a large permeability, which promotes surface rewetting by liquids, preferably for boiling heat transfer. It is also seen that the nanoparticles prefer to agglomerate on the tops of the micro pin fins, generating dense coatings (see Figure S3 in the Supporting Information for SEM characteristics of the coatings). Although numerous pore structures exist on the coatings, they are not expected to promote nucleation too much because of a large thermal resistance from the pin root to the pin top. However, the coating is supposed to alter the bubble departure behavior and also affect the critical heat flux.

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Pool Boiling Measurement. Figure 2 schematically shows the pool boiling setup, which mainly consists of a heating unit, a boiling unit, a data acquisition unit, and a bubble visualization unit. The boiling chamber is made of transparent poly(methyl methacrylate), having a size of 120 mm × 120 mm × 110 mm in length, width, and height, respectively. Joule heating was employed to heat the surface. Accordingly, two copper wires were soldered on two opposite sides of the surface by an ultrasonic bonding method, and the two wires were connected with a DC power supply (Agilent N5715A). To measure the boiling surface temperature, a T-type thermocouple was attached to the center of the backside of the surface with a thermally conductive adhesive. In the end, the surface packaged with copper wires and thermocouple was glued with RTV silicone on a plexiglass base. A high-speed camera (Nac Memerecam HX-6E) was used to record the bubble dynamics with 1000 frames per second.

In the experiments, around 1.5 L FC-72 was poured into the boiling chamber and was then heated up by an auxiliary heater, reaching the saturation state at atmospheric pressure. The liquid temperature was monitored by a T-type thermocouple. The power that heated the surface was characterized by voltage multiplied by current controlled by the DC power supply. The case-by-case voltage increase varied with the heat flux ranges. At low heat fluxes where isolated bubbles could be recognized, a small voltage step of 0.5 V was used, while at moderate-to-high heat fluxes where only large coalesced bubbles were recognized, a large voltage step of 2 V was applied. However, as the critical heat flux was approaching, a voltage step of 0.5 V was reused. In each case, data were recorded at a steady state when the temperature variation was less than 0.2 °C in 30 s. Once the wall temperature increased abruptly or the current decreased
sharply, the power supply was stopped immediately and the critical heat flux was confirmed in this case. Data reduction and uncertainty analyses are provided in section S2 in the Supporting Information. The maximum uncertainties of the heat flux and the heat transfer coefficient were 6.1 and 9.5% in the nucleate boiling regime, respectively.

**RESULTS AND DISCUSSION**

**Experiment Validation and Repeatability.** To make sure that the experimental setup worked correctly, saturated pool boiling of FC-72 on a smooth silicon surface (SS) was tested first of all and then the obtained pool boiling curve was compared with those in the literature (see Figure S3 in the Supporting Information), presenting a good agreement. In addition, the present critical heat flux on SS is found to be 14.52 W/cm², which is very close to the prediction of 13.68 W/cm² by Zuber’s model. Therefore, the present setup is reliable to do further experiments.

Then, the saturated pool boiling of FC-72 on the prepared micro-pin-fin surfaces with/without nanoparticles was tested. Repeatability of results is an important issue that should be carefully addressed. In the present study, the measurement was repeated three times on each surface (see Figure S4 in the Supporting Information). It is seen that all measurements have very good repeatability, and the results obtained the second time were selected for comparison.

**Micro Pin Fin and Nanoparticle Effect on Boiling Performance.** Figure 3a demonstrates the saturated boiling curves on the micro-pin-fin surfaces (CPF-1, SPF-1, SPF-2) and the smooth surface (SS). It is seen that compared with the smooth surface, the micro pin fins considerably move the curve to the left, meaning that the same superheat corresponds to a larger heat flux on the micro-pin-fin surfaces. The critical heat flux (CHF) on SS, CPF-1, SPF-1, and SPF-2 is 14.52, 26.56, 26.48, and 23.91 W/cm², respectively. Accordingly, a maximum CHF enhancement of 69.1% is achieved on CPF-1 in comparison to SS, while CPF-1 and SPF-1 present almost identical CHF but higher than that on SPF-2. The critical heat flux enhancement mechanism will be discussed in detail in a later section. However, surface wickability that characterizes liquid rewetting ability plays an essential role in determining the critical heat flux. Experimental measurements indicate that the micro-pin-fin surfaces have much larger wickability than the smooth surface, while among the micro-pin-fin surfaces, SPF-2 has a lower wickability than the other two surfaces. Figure 3b quantitatively compares the heat transfer coefficient on the micro-pin-fin surfaces and the smooth surface. Obviously, the heat transfer is augmented by the micro pin fins, especially in the nucleate boiling regime. However, the square micro pin fins (SPF-1 and SPF-2) perform better than the circular micro pin fins (CPF-1). Xu et al. observed and confirmed that bubbles preferred to nucleate on corners in triangular channels. Then, it is conjectured that because of the sharper corners on the square micro pin roots, bubble nucleation might be more intensive there. However, the fins present almost no effect on the heat transfer in the natural convection regime (q < 2 W/cm²), which is widely observed. This is probably because the pins are fully immersed in a stationary thermal boundary layer where heat transfer is dominated by heat conduction. Natural convection takes place in a region above the thermal boundary layer, which then is little affected by the immersed pins. It is also found that with increasing heat flux, the boiling heat transfer is largely enhanced by the micro pin fins. Actually, at higher heat fluxes, more nucleation sites can be activated and the bubble dynamics become more violent, inducing intensive liquid turbulence, which finally enhances heat transfer more vigorously. In the present study, the maximum heat transfer...
coefficients obtained are 0.42, 1.06, 1.43, and 1.23 W/(cm²·K) on the SS, CPF-1, SPF-1, and SPF-2, respectively.

This study successively and innovatively deposited copper nanoparticles on the micro-pin-fin surfaces, obtaining micro/nanocomposite structures. It is then of interest to reveal the effect of these nanoparticles on the boiling performance. Figure 4 compares the boiling curves on the micro-pin-fin surfaces with/without nanoparticles. The comparison shows that the nanoparticles further improve the critical heat flux (CHF). For example, the CHFs on SPF-1-NP1 and SPF-1-NP2 are 30.01 and 29.24 W/cm², respectively, while the CHF on SPF-1 is 26.45 W/cm². Displacement of the boiling curves by nanoparticles indicates the effect of nanoparticles on heat transfer, i.e., left and right displacements corresponding to enhancement and deterioration, respectively. It is seen that the effect of the nanoparticles on heating heat transfer generally depends on the micro-pin-fin geometries and heat flux. On the circular-micro-pin-fin surface (CPF-1 in Figure 4a), the nanoparticles further enhance boiling heat transfer, especially at heat fluxes smaller than 20 W/cm². Comparatively, on the square-micro-pin-fin surface (SPF-1 and SPF-2 in Figure 4b,c, respectively), the nanoparticles have little effect on boiling heat transfer and even show a slight deterioration on SPF-2. This inconsistent effect can also be found in the literature. For example, Rahman et al. 40 compared pool boiling curves of micro-pin-fin surfaces with and without nanostructures, and heat transfer was found to be deteriorated by the nanostructures. In contrast, Liu et al. 41 and Zhou et al. 53 reported heat transfer enhancement by nanostructures on micro-pin-fin surfaces. Therefore, it is essential to find clues to account for the effect of nanoparticles on heat transfer, and bubble dynamics is an important clue.

Quantitative Bubble Dynamics Study. Although boiling heat transfer enhancement on structured surfaces is well documented, the physical mechanisms responsible for the enhancement are not well understood. Kim et al. 61 carefully explored the mechanism of nucleate boiling enhancement of FC-72 on microporous surfaces. It was concluded that the enhancement was through increased latent heat transfer in the low-heat-flux region and through increased convection heat transfer in the large-heat-flux region, both of which depended on bubble dynamics, e.g., bubble departure diameter, bubble departure frequency, and active nucleation site density. In addition, many proposed heat transfer modes during nucleate boiling, e.g., transient conduction, 62 microconvection, 63 and microlayer evaporation, 64 are strongly related to the bubble dynamics. However, regarding the boiling of FC-72, which has a small surface tension, it is difficult to accurately extract the bubble dynamics because of violent boiling and intense bubble interactions, resulting in challenges in obtaining accurate and adequate bubble dynamics data. Therefore, in this study, the quantity of heat flux was carefully controlled, and exactly isolated bubbles were carefully recognized from the captured visualizations. The bubble dynamics are then compared among the smooth surface and the micro-pin-fin surfaces with and without the nanoparticles, revealing the effect of micro pin fins and nanoparticles. Subsequently, its coupling with heat transfer is discussed.

Figure 5 compares a bubble growth process on the smooth surface (SS) and the micro-pin-fin surfaces (CPF-1, SPF-2) at similar heat fluxes. Similar bubble growth characteristics appear. The growth characteristics are also similar to those reported on hydrophilic surfaces (surfaces with low receding contact angles). 65,66 The bubble first experiences a fast growth process, e.g., 0–6, 0–3, and 0–2 ms on SS, CPF-1, and SPF-2, respectively. The bubble then shows a quick shrinking process of the gas—liquid—solid phase line because buoyancy begins to distort the bubble shape. The bubble finally departs when the buoyancy completely overcomes the surface tension that holds the bubble and is normally proportional to the sine of the contact angle at departure (θd). The micro pin fins considerably shorten the bubble growth period as shown in Figure 5, probably because, on the one hand, a smaller θd is seen on the micro-pin-fin surfaces, decreasing the surface tension force, and on the other hand, the micro pin fins accelerate the shrinking of the gas—liquid—solid phase contact line.

The bubble growth dynamics are also compared between the micro-pin-fin surface with and without the nanoparticles to illustrate the effect of the nanoparticles. By carefully extracting bubble dynamics information from a large number of bubble visualizations, it is generally found that the nanoparticles may affect the bubble growth period and the bubble departure diameter. For example, Figure 6 demonstrates a bubble growth process recognized from bubble visualizations on CPF-1, CPF-1-NP1, and CPF-1-NP2. The bubble is subjected to the same process as that described in Figure 5, and in this case, the nanoparticles appear to further decrease the bubble growth period (e.g., 5 ms on CPF-1 against 3 ms on CPF-1-NP2), which is probably because the nanoparticles beneath the bubble make the gas—liquid—solid phase contact line move inward more quickly. However, it is worth noting that this
The finding is not completely universal in the present study, but seems to depend on specific nucleation sites and micro-pin-fin surfaces. Therefore, the bubble growth process is also carefully compared on SPF-1 and SPF-2 (see Figures S5 and S6, respectively, in the Supporting Information). It is found that on SPF-1, the nanoparticles only slightly affect the bubble growth period (see Figure S5). The growth period can slightly decrease on one site (e.g., 4 ms on SPF-1 against 3 ms on SPF-1-NP2), while it slightly increases on another site (e.g., 4 ms on SPF-1 against 5 ms on SPF-1-NP2). However, on SPF-2 (see Figure S6), the nanoparticles considerably increase the bubble growth period on one site (e.g., 3 ms on SPF-2 against 6 ms on SPF-2-NP1), while on another site, the growth period is almost identical. Usually, a long growth period corresponds to a large departure diameter and vice versa.

The above discussion involves the bubble growth characteristics based on a few recognized isolated bubbles. In fact, a complete bubble cycle also includes a waiting time that is not particularly compared at present. In what follows, the bubble departure diameter ($D_b$) and bubble departure frequency ($f_b$, reciprocal of the bubble cycle) are studied in detail. In the practical measurements, FC-72 bubble coalescence extensively occurs especially on the nonsmooth surfaces even at low heat fluxes and many bubbles are prone to be blocked by surrounding bubbles. Therefore, identification of isolated bubbles from a few hundreds of images should be done with utmost care and patience. In addition, to measure the bubble departure diameter and the bubble departure frequency as accurately as possible, the isolated bubbles were measured on different nucleation sites at each heat flux, and even on the same site, more than 15 successive bubbles were measured. The uncertainty of the bubble departure diameter was estimated as ±12.2 to ±23.2% on SPF-2 (see section S4 in the Supporting Information for more details). These measured bubble departure diameters and their corresponding bubble frequencies were compared with a few models (see Figure S7).

It is found that the diameter and the frequency follow inversely proportional trends, wherein the frequency increases with decreasing bubble diameter. The Jakob model$^{67}$ could roughly predict this relationship, which means that the product of diameter and frequency tends to be a constant that depends on the liquid properties.

$$D_b f_b = \left( \frac{\sigma_{lv} g (\rho_l - \rho_v)}{\rho_l^2} \right)^{1/4}$$

where $\rho_l$, $\rho_v$, $\sigma_{lv}$, and $g$ are the liquid density, vapor density, liquid–vapor surface tension, and gravitational acceleration, respectively. These bubbles work synergistically to affect heat transfer performance. To better understand the coupling between bubble dynamics and heat transfer, an average value, characterizing the comprehensive bubble dynamics, should be compared.

In the present study, the average bubble departure diameter ($D_{b,a}$) and the average bubble departure frequency ($f_{b,a}$) were calculated by data shown in Figure S7, which are compared in

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**Figure 6.** Comparison of bubble growth dynamics on CPF-1 (without nanoparticles) and CPF-1-NP1 and CPF-1-NP2 (with nanoparticles).

**Figure 7.** Comparison of the average bubble departure diameter against the average bubble departure frequency. Black line: Jakob model.$^{67}$

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Figure 7, indicating the effect of micro pin fins and nanoparticles. It is seen that bubbles on the micro-pin-fin surfaces have smaller departure diameters and higher departure frequencies than those on the smooth surface (see Figure 7a). However, the effect of nanoparticles varies on different micro-pin-fin surfaces. On CPF-1 (see Figure 7b), the nanoparticles promote bubble departure with smaller diameters, while on SPF-1 and SPF-2 (see Figure 7c,d), the nanoparticles only exert slight effects on the bubble departure diameter and the bubble departure frequency (the data points are roughly distributed within the same region), except on SPF-2-NP1, where the nanoparticles even slightly inhibit bubble departure.

However, the bubble dynamics also depends on heating conditions. It is preferable to compare it under the same heating conditions. Therefore, the bubble dynamics and its corresponding heat flux are compared, and bubble visualizations at the same heat flux are also presented. All of these factors explain the mechanism of how heat transfer is affected by the micro pin fins and the nanoparticles. Figure 8a compares the heat flux–bubble dynamics coupling and bubble visualizations on the smooth surface and the micro-pin-fin surfaces (SPF-1, SPF-2, and CPF-1). It is seen that at the same heat flux, the micro-pin-fin surfaces have smaller bubble departure diameters and higher bubble departure frequencies than the smooth surface. Furthermore, SPF-1 has smaller bubble departure diameters and higher bubble departure frequencies than SPF-2, while SPF-2 has smaller bubble departure diameters and higher bubble departure frequencies than CPF-1 at the same heat fluxes, e.g., $q = 3.57$ and $4.6$ W/cm$^2$. It is also found that the micro-pin-fin surfaces provide larger active nucleation site densities than the smooth surface, but the exact quantities are not compared because the number of bubbles could not be correctly extracted from the visualization, especially for the micro-pin-fin surfaces where bubble interactions were vigorous. These findings offer convincing explanations for the heat transfer enhancement by the micro pin fins as discussed in Figure 4.

Figure 8b compares the heat flux–bubble dynamics coupling and bubble visualizations on CPF-1 with and without the nanoparticles, which confirms that in this case, the nanoparticles could promote bubble departure at the same heat flux, e.g., $q = 5.0$ W/cm$^2$. It is hard to conclude whether the nanoparticles could increase the active nucleation site density because of a large area where isolated bubbles cannot be recognized, but it seems that the active nucleation site density is not affected by the nanoparticles too much. The enhanced bubble dynamics coincide with the augmented heat transfer presented in Figure 5a. The heat flux–bubble dynamics coupling and bubble visualizations are also compared concerning the effect of nanoparticles on heat transfer on SPF-1 and SPF-2 (see Figures S8 and S9 in the Supporting Information). It also confirms that the nanoparticles slightly affect the bubble dynamics on SPF1 and SPF2, except SPF-2-NP1, where the nanoparticles even postpone the bubble departure, which accounts for the heat transfer performance in Figure 5a,b.

The above findings confirm that boiling heat transfer strongly depends on bubble dynamics. Smaller bubble departure diameters and higher bubble departure frequencies induce better heat transfer performance and vice versa. Accordingly, the effect of nanoparticles on boiling heat transfer is determined by its manipulation of the bubble dynamics. The bubble departure diameter is dependent on exerted forces, i.e., a surface tension force that pins the bubble onto the surface and a buoyancy force that drags the bubble away from the surface. It is conjectured that nanoparticles can affect the

Figure 8. Heat flux ($q$)–average bubble diameter ($D_{ba}$)–average bubble frequency ($f_{ba}$) coupling and bubble visualizations. Black line: Jakob model.67
surface tension force in two ways. On the one hand, nanoparticles can enlarge the three-phase contact line, which represents an enlarged surface tension force, inducing a pinning effect. On the other hand, nanoparticles can modulate the dynamic contact angle during bubble growth. A decreased contact angle results in a decreased surface tension force, and vice versa. Therefore, the final effect of nanoparticles on the surface tension force is a trade-off of these two aspects. If the surface tension force is decreased by the nanoparticles, then the bubble can depart with a smaller diameter, while if the surface tension force is increased by the nanoparticles, then the bubble departs with an increased diameter.

**Critical Heat Flux Study.** Critical heat flux is an important topic. In practical applications, if heat flux is beyond the critical heat flux, heat transfer will deteriorate sharply, which usually results in an abrupt increase in device temperature, causing a serious accident. Therefore, it is important to investigate the mechanism that triggers critical heat flux. To date, several mechanistic models have been proposed. These models are generally suitable to account for the critical heat flux on a smooth surface. For example, the predicted critical heat fluxes on a smooth surface are 13.69, 12.65, 11.70, and 19.40 W/cm² by Zuber’s hydrodynamic instability model, the macrolayer dryout model, the hot/dry spot model, and the force balance model, respectively, while the experimental result is 14.52 W/cm² in this study. Even though these models are built from different perspectives, the common basic concept is that the critical heat flux is triggered because of interrupted liquid supply. For example, the instability model assumes that the critical heat flux occurs when the Helmholtz instability reaches a critical condition when vapor merges and collapses to prevent liquid from flowing onto surfaces, while the macrolayer dryout model postulates that an insufficient liquid feeding of a liquid film on surfaces induces the critical heat flux. Similarly, irreversible growth of dry spots prevails over liquid supply, resulting in the critical heat flux, while bubble spreading driven by forces prevents liquid from rewetting surfaces, triggering the critical heat flux. Therefore, it is evident that the critical heat flux should be improved by enhancing the liquid rewetting ability. Anh et al. confirmed that enhanced capillary wicking action of micro/nanostructures corresponds to enhanced critical heat flux. Then, Rahman et al. proposed a method to quantitatively measure the capillary wicking action, namely, wickability, on structured super-hydrophilic surfaces and presented a clear relationship between the wickability and the critical heat flux on the structured surfaces. Inspired by Anh et al. and Rahman et al., subsequent studies were extensively carried out. A general expression concerning the critical heat flux on a structured surface can be formulated as

$$\text{CHF} = \text{CHF}_{\text{ss}} + q_{\text{gain}}$$  \hspace{1cm} (2)

where $\text{CHF}_{\text{ss}}$ is the critical heat flux on a smooth surface, which was predicted by the Kandlikar model and the Zuber model in Anh et al. and Rahman et al., respectively, and $q_{\text{gain}}$ is the critical heat flux gained by enhanced wickability.

In the present study, the wickability is measured by the method proposed by Rahman et al. A microcapillary tube with an inner diameter of 300 μm and an outer diameter of 600 μm was used. A syringe was connected to fill the microcapillary tube initially with a certain level of the liquid FC-72. The test surfaces were placed on an adjustable moving stage that was carefully controlled to make the surface touch the mouth of the microcapillary tube. A high-speed camera synchronically captured the change of the liquid level in the tube (see videos in the Supporting Information). Figure 9a shows the liquid level changing with time on SPF-2 as an example, and Figure 9b compares the liquid height drop with time on all test surfaces (see Section S5 in the Supporting Information).
where $A_w$ is the wetted area, which is assumed to be the outer bottom area of the microcapillary tube, based on the present visualization and the measurements for FC-72 in the study of Rahman et al.\textsuperscript{40} $A_i$ is the inner bottom area of the microcapillary tube, and $\Delta h$ is the liquid height drop within an elapsing time $t$. eq 3 indicates that the wicking flux is time dependent, and the initial wicking flux at $t = 0$ (the start of liquid wicking) is selected in this study. Allred et al.\textsuperscript{75} modeled the liquid wicking in micro pin fins as inward radial flow in a porous medium. A theoretical solution to the wickability was derived by solving the one-dimensional Darcy equation, which is compared with the present measurements, as shown in Figure 9c. It is seen that the present measurement agrees well with the theoretical model, confirming the reliability and accuracy of the measurement.

Figure 10 compares the critical heat flux against the wicking flux. It is seen that the critical heat flux has a good linear relationship with the wicking flux, which is consistent with the finding in ref\textsuperscript{40}. The offset (vertical axis intercept) of the fitting line (black dashed line) represents a predicted critical heat flux on an absolutely smooth surface, i.e., 13.68 W/cm$^2$, which is extremely close to Zuber’s prediction of 13.69 W/cm$^2$. This proves the rationality of the fitting line to some extent. The fitting line is described as

\[
CHF = CHF_{\text{ss}} + q_{\text{gain}} = CHF_{\text{ss}} + C \rho_l h_l / \phi_w
\]

where $\rho_l = 1620$ kg/m$^3$ and $h_l = 84500$ J/kg are the liquid density and latent heat, respectively. $C$ is a coefficient that accounts for the difference between the real wicking flux at critical heat flux and the measured wicking flux under room temperature conditions, which is suggested to be 0.081.

Even though eq 4 gives a relatively good prediction of the critical heat flux on structured surfaces in the present study, it is still seen that some data scatter from the fitting line, especially the data on micro-pin-fin surfaces with the nanoparticles, e.g., CPF-1-NP1 and SPF-1-NP1. Similarly, Liu et al.\textsuperscript{41,76} also found that the wicking flux is an important factor to enhance critical heat flux, but it cannot completely account for the enhancement, particularly on surfaces with rather different characteristics. Therefore, it is conjectured that besides the enhanced wicking flux, there must exist other mechanisms that affect the critical heat flux on the structured surfaces. Liu et al.\textsuperscript{41,76} further considered the regulation of micro/nanostructures on bubble dynamics at critical heat flux and proposed a model that incorporates wicking fluxes and bubble departure frequencies. Recently, Hu et al.\textsuperscript{77} proposed a coupled wicking and evaporation model to predict the critical heat flux on structured surfaces, which was great inspiration for the present study. This model further considers the evaporation beneath bubbles. The critical heat flux is a result of the competition between the wicking and the evaporation. Figure 11 illustrates a schematic diagram of the critical heat flux mechanism dominated by wicking and evaporation. Wicking facilitates rewetting of the surface by absorbing liquid from the surrounding pool, while the evaporation occurs on an ultrathin liquid film formed on structures beneath the large coalesced bubbles, which consumes the liquid. The practical wicking flux at critical heat flux increases with increasing dry spot diameter ($d_{\text{dry}}$) because the increasing dry spot diameter decreases the liquid imbibition distance from the bulk surrounding the pool to the dry spot, resulting in a smaller viscous resistance. In contrast, the increasing dry spot diameter leads to a decreasing area for evaporation, resulting in a lower evaporation flux. Therefore, the critical heat flux is triggered under a condition when the wicking flux balances with the evaporation flux.

Hu et al.\textsuperscript{77} proposed two parameters to define the wicking flux and the evaporation flux, which are characteristic wicking flux ($\phi_{\text{w,clch}}$) and characteristic evaporation flux ($\phi_{\text{e,clch}}$). Then, the critical heat flux gain is expressed as

\[
q_{\text{gain}} = \rho_l h_l / \phi_{\text{w,clch}} \ln(d_b / d_{\text{dry}}) = \rho_l h_l / \phi_{\text{e,clch}} \left[1 - \left(\frac{d_{\text{dry}}}{d_b}\right)^2\right]
\]

The characteristic wicking flux was analytically obtained by solving the Brinkman equation as\textsuperscript{77}

![Figure 11. Schematic diagram of the critical heat flux mechanism (d$_{\text{cl}}$: diameter of large coalesced bubbles, d$_{\text{dry}}$: diameter of the dry spot). Pin fins and bubbles are not drawn to scale.](https://dx.doi.org/10.1021/acs.langmuir.0c02860)
where \( K \) and \( \varepsilon \) are the surface permeability and porosity, respectively, \( h \) is the height of a micro pin fin, \( P_c \) is the capillary pressure, and \( \rho_f, \rho_g, \sigma_{lv}, \) and \( g \) are the liquid density, vapor density, liquid dynamic viscosity, liquid–vapor surface tension, and gravitational acceleration, respectively. In the present study, the permeability of CPF-1 and SPF-1 was calculated by the model proposed by Sangani and Acrivos, while the permeability of SPF-2 and the micropost surface was calculated by the model proposed by Drummond and Tahit, considering the configuration of micro pin fins. The capillary pressure was calculated as the free-energy change per unit volume for liquid wetting the surface (see S6 in the Supporting Information for details).

The characteristic evaporation flux was derived based on an equilibrium meniscus formed between micro pin fins beneath bubbles where a thermal network model was applied that has balanced thermal conduction across the liquid film and evaporation across the liquid–vapor interface. The characteristic evaporation flux was derived as

\[
\dot{q}_{\text{ev,ch}} = \frac{2\pi \varepsilon \sigma_{lv} h}{\mu_1} \left[ 1 - \tan \left( \sqrt{\frac{\varepsilon}{K_h}} \right) \right] \\
/ \left( \pi \sqrt{\varepsilon / g / (\rho_f - \rho_g) \right)^2}
\]

(6)

where \( R \) is the radius of the equilibrium meniscus, \( \delta(y) \) is the meniscus profile (the liquid film thickness) with respect to the position along the pin fin height, \( k_i \) is the liquid thermal conductivity, \( \theta_{ns} \) is the receding contact angle, \( d \) and \( p \) are the diameter of a micro pin fin and the pitch between neighboring pin fins, respectively, and \( h_y \) is the evaporation heat transfer coefficient. In the present study, the receding contact angle is assumed to be zero and the meniscus profile is assumed to be a circular profile. The projected surface area \( (p^2 \text{ in eq 7}) \) that is involved in the evaporation around a single micro pin fin is revised. It is assumed that a micro pin fin is surrounded by liquid with an equilibrium meniscus that has a radius of \((p - d_{ns}) / 2 \cos(\theta_{ns}) \) for staggered micro pin fins, \( d_{ns} \) is assumed to be \( 2/0.5 \pi d \) for the present square micro pin fin and circular micro pin fin, respectively. The projected surface area is then revised as \( \pi (p/2)^2 - \pi (p/2)^2 \) for the present square-micro-pin-fin surfaces (SPF-1 and SPF-2) and the circular-micro-pin-fin surface (CPF-1), respectively.

Figure 12 compares the experimental critical heat flux gain with the predicted value given by eq 5. The experimental gain was obtained by deducting the critical heat flux on a smooth surface predicted by the Zuber from the critical heat flux on the structured surfaces. It is seen that the coupled wicking and evaporation model has a relatively good consistency with the experimental values (less than 10% of error), proving that the wicking and evaporation work synergistically to determine the critical heat flux on structured surfaces. It is also interesting that the characteristic wicking flux is much larger than the evaporation flux, meaning that a very large dry spot will form when triggering the critical heat flux. This conclusion is fully consistent with the experimental observations. It should be noted that only the experimental values on the micro-pin-fin surfaces without the nanoparticles are compared because the presence of the nanoparticles probably distorts the meniscus profile, which cannot be mathematically estimated as a circular profile. As a consequence, the characteristic wicking flux and the characteristic evaporation flux cannot be estimated by eqs 6 and 7, respectively. However, the coupled model provides some clues to the further critical heat flux enhancement by the nanoparticles (the data scattering in Figure 10, e.g., CPF-1-NP1 and SPF-1-NP1). This is probably because the nanoparticles may distort the liquid meniscus to some extent, enlarging the thin-film meniscus interface area so that the evaporation is enhanced. Therefore, although the micro-pin-fin surfaces with the nanoparticles, i.e., CPF-1-NP1 and SPF-1-NP1, have lower measured wicking flux (see Figure 10), the critical heat flux is still further enhanced by the nanoparticles.

### CONCLUSIONS

In this study, nanoparticle-assisted pool boiling of FC-72 was experimentally studied on micro-pin-fin-surfaces (CPF-1, SPF-1, and SPF-2). In comparison to a smooth surface, the micro pin fins increase the heat transfer coefficient by more than 200% and the critical heat flux by 65–83%, while the nanoparticles can further enhance the critical heat flux and the heat transfer coefficient by up to 24% and more than 20%, respectively. The results of bubble dynamics confirm that the bubble departure diameter is inversely proportional to the bubble frequency, which considerably affects the heat transfer. The heat transfer enhancement on the micro-pin-fin surfaces is attributed to increased active nucleation site density and positive manipulation of the bubble dynamics, i.e., smaller bubble departure diameter and higher bubble frequency, while the nanoparticle-assisted heat transfer performance on the micro-pin-fin surfaces depends on the bubble dynamics regulated by the nanoparticles. For example, a further positive manipulation induces further heat transfer enhancement by the nanoparticles on CPF-1, while a weak manipulation slightly affects the heat transfer by the nanoparticles on SPF-1. The mechanism of the critical heat flux enhancement was investigated in detail. The wickability measured at room temperature indicates that the wicking flux intensification, characterizing the liquid rewetting ability, is an essential mechanism that corresponds to the critical heat flux enhancement on the micro-pin-fin surfaces. Further model analyses show that the critical heat flux on structured surfaces is determined by both the wicking flux and the evaporation flux beneath large coalesced bubbles. It is conjectured that the
nanoparticles may distort the liquid meniscus formed between the micro pin fins, which can enlarge the thin-film interface and then enhance the evaporation flux. The enhanced evaporation flux leads to further enhancement of critical heat flux by the nanoparticles.

**ASSOCIATED CONTENT**

* Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.langmuir.0c02860.

Electrostatic deposition method; data reduction and uncertainty analysis; experimental validation and repeatability; bubble dynamics; wickability measurement (see videos); and derivation of capillary pressure on surfaces with staggered micro pin fins (PDF)

Video SS—Liquid height changing with time on the smooth surface SS (AVI)

Video CPF-1—Liquid height changing with time on the micro-pin-fin surface CPF-1 (AVI)

Video SPF-1—Liquid height changing with time on the micro-pin-fin surface SPF-1 (AVI)

Video SPF-2—Liquid height changing with time on the micro-pin-fin surface SPF-2 (AVI)

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Author Contributions
Z.C. and B.L. contributed equally to this work. Z.C. processed the data and wrote the manuscript with help from Z.W. Z.C. and B.L. performed the boiling experiments and wickability measurement. B.L., Y-H.Z., and J-J.W. fabricated the micro-pin-fin surfaces. C.P., M.E.M., and K.D. conducted the electrostatic deposition. Z.W., Y-H.Z., J-J.W., and B.S. were academic supervisors and led the boiling-related research projects. All authors have given approval to the final version of the manuscript.

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**ABBREVIATIONS USED**

CHF critical heat flux

CPF circular micro pin fin

HTC heat transfer coefficient

NP nanoparticle deposition

SEM scanning electron microscopy

SPF square micro pin fin

**REFERENCES**

(1) Alkharabsheh, S.; Fernandes, J.; Gebrehiwot, B.; Agonafer, D.; Ghose, K.; Ortega, A.; Yoshi, Y.; Sammakia, B. A Brief Overview of Recent Developments in Thermal Management in Data Centers. J. Electron. Packag. 2015, 137, No. 040801.

(2) Kheirabadi, A. C.; Groulx, D. Cooling of server electronics: A design review of existing technology. Appl. Therm. Eng. 2016, 105, 622–638.

(3) Zhu, J.-F.; Li, X.-Y.; Wang, S.-L.; Yang, Y.-R.; Wang, X.-D. Performance comparison of wavy microchannel heat sinks with wavy bottom rib and side rib designs. Int. J. Therm. Sci. 2019, 146, No. 106068.

(4) Cao, Z. Pool Boiling on Structured Surfaces: Heat Transfer and Critical Heat Flux—Experiments and Mechanistic Modelling. Doctor Dissertation, Lund University: Lund, 2019.

(5) Mudawar, I. Assessment of High-Heat-Flux Thermal Management Schemes. IEEE Trans. Compon., Packag., Manuf. Technol. 2001, 24, 122–141.

(6) Kuncoro, I. W.; Pambudi, N. A.; Biddinika, M. K.; Widiastuti, I.; Hijriawan, M.; Wibowo, K. M. Immersion cooling as the next technology for data center cooling: A review. J. Phys. Conf. Ser. 2019, 1402, No. 044057.

(7) El-Genk, M. S. Immersion cooling nucleate boiling of high power computer chips. Energy Convers. Manage. 2012, 53, 205–218.

(8) Birbarah, P.; Gebrael, T.; Foulkes, T.; Stillwell, A.; Moore, A.; Pilawa-Podgurski, R.; Miljkovic, N. Water immersion cooling of high power density electronics. Int. J. Heat Mass Transfer 2020, 147, No. 118918.

(9) Hsu, Y.-T.; Li, J.-X.; Lu, M.-C. Enhanced immersion cooling using two-tier micro- and nano-structures. Appl. Therm. Eng. 2018, 131, 864–873.

(10) Wang, Y.; Pambudi, N. A.; Bugis, H.; Kuncoro, I. W.; Setiawan, N. D.; Hijriawan, M.; Rudiyanto, B.; Basori, B. Preliminary experimental of GPU immersion-cooling. E3S Web Conf. 2019, 93, 03003.
(11) Ahangar Zonouzi, S.; Aminfar, H.; Mohammadpourfard, M. A review on effects of magnetic fields and electric fields on boiling heat transfer and CHF. *Appl. Therm. Eng.* 2019, 151, 11–25.

(12) Bourdon, B.; Rioboo, R.; Marengo, M.; Gosselin, E.; Coninck, J. D. Influence of the wettability on the boiling onset. *Langmuir* 2012, 28, 1618–1624.

(13) Deng, D.; Wan, W.; Feng, J.; Huang, Q.; Qin, Y.; Xie, Y. Comparative experimental study on pool boiling performance of porous coating and solid structures with reentrant channels. *Appl. Therm. Eng.* 2016, 107, 420–430.

(14) Jun; S.; Kim, J.; Son, D.; Kim, H. Y.; You, S. M. Enhancement of Pool Boiling Heat Transfer in Water Using Sintered Copper Microporous Coatings. *Nucl. Eng. Technol.* 2016, 48, 932–940.

(15) Ha, M.; Graham, S. Pool boiling characteristics and critical heat flux mechanisms of microporous surfaces and enhancements through structural modification. *Appl. Phys. Lett.* 2017, 111, No. 091601.

(16) Pham, Q. N.; Zhang, S.; Hao, S.; Montazeri, K.; Lin, C. H.; Lee, J.; Mohraz, A.; Won, Y. Boiling Heat Transfer with a Well-Ordered Microporous Architecture. *ACS Appl. Mater. Interfaces* 2020, 12, 19174–19183.

(17) Ji, X.; Xu, J.; Zhao, Z.; Yang, W. Pool boiling heat transfer on uniform and non-uniform porous coating surfaces. *Exp. Therm. Fluid Sci.* 2013, 48, 198–212.

(18) Sarangi, S.; Weibel, J. A.; Garimella, S. V. Effect of particle size on surface-coating enhancement of pool boiling heat transfer. *Int. J. Heat Mass Transfer* 2015, 81, 103–113.

(19) Sarangi, S.; Weibel, J. A.; Garimella, S. V. Quantitative Evaluation of the Dependence of Pool Boiling Heat Transfer Enhancement on Sintered Particle Coating Characteristics. *J. Heat Transfer* 2017, 139, No. 021502.

(20) EL-Genk, M. S.; Ali, A. F. Enhanced nucleate boiling on copper micro-porous surfaces. *Int. J. Multiphase Flow* 2010, 36, 780–792.

(21) Furberg, R.; Palm, B. Boiling heat transfer on a dendritic and micro-porous surface in R134a and FC-72. *Appl. Therm. Eng.* 2011, 31, 3595–3603.

(22) Cao, Z.; Wu, Z.; Sundén, B. Heat transfer prediction and critical heat flux mechanism for pool boiling of NOVEC-649 on microporous copper surfaces. *Int. J. Heat Mass Transfer* 2019, 141, 818–834.

(23) Wu, Z.; Cao, Z.; Sundén, B. Saturated pool boiling heat transfer of acetone and HFE-7200 on modified surfaces by electrophoretic and electrochemical deposition. *Appl. Energy* 2019, 249, 286–299.

(24) Zou, A.; Singh, P. D.; Maroo, C. S. Early evaporation of microlayer for boiling heat transfer enhancement. *Langmuir* 2020, 36, 9643–9648.

(25) Liu, B.; Liu, J.; Enright, R.; Wang, E. N. Saturated surfaces for enhanced enhanced pool boiling heat transfer. *Appl. Mater. Interfaces* 2020, 12, 104603.

(26) Shin, S.; Choi, G.; Rallabandi, B.; Lee, D.; Shim, D. I.; Kim, B. S. Electrophoretic deposition surfaces to enhance HFE-7200 pool boiling heat transfer critical heat flux. *Int. J. Heat Transfer* 2021, 37, 106117.

(27) Prakash Chakrapani Gunarasan, J.; Ravindran, P. Significance of microwave surface modification for enhanced pool boiling heat transfer. *Int. J. Therm. Sci.* 2021, 1618, 1–17.

(28) Prakash Chakrapani Gunarasan, J.; Ravindran, P. Significance of microwave surface modification for enhanced pool boiling heat transfer. *Int. J. Therm. Sci.* 2021, 1618, 1–17.

(29) Su, C.-Y.; Yang, C.-Y.; Jhang, B. W.; Hsieh, Y. L.; Sin, Y. Y.; Zhang, Y.; Wu, Z.; Pham, A.; Wang, W.; Yan, Z.; Wei, J.; Sundén, B. Pool boiling heat transfer of N-pentane on micro/nanostructured surfaces. *Langmuir* 2019, 35, 12689–12693.

(30) Huang, C. C. Pool Boiling Heat Transfer Enhanced by Fluorinated surface topology. *Adv. Mater. Interfaces* 2020, 7, 2000482.

(31) Li, J.; Fu, W.; Zhang, B.; Zhu, G.; Miljkovic, N. Ultrascalable Three-Tier Hierarchical Nanoengineered Surfaces for Optimized Boiling. *ACS Nano* 2019, 13, 14080–14093.

(32) Liu, M.; Lu, K.; Li, X.; Liu, H.; Jing, D. Light-induced enhancement of critical heat flux on TiO2 coatings with specific surface topology. *Appl. Therm. Eng.* 2020, 174, No. 115333.

(33) Liu, M.; Lu, K.; Liu, X.; Liu, H.; Jing, D. Light-induced enhancement of critical heat flux on TiO2 coatings with specific surface topology. *Appl. Therm. Eng.* 2020, 174, No. 115333.

(34) Chen, R.; Lu, M. C.; Srinivasan, V.; Wang, Z.; Cho, H. H.; Majumdar, A. Nanowires for Enhanced Boiling Heat Transfer. *Nano Lett.* 2009, 9, 548–553.

(35) Shim, D. I.; Choi, G.; Lee, N.; Kim, T.; Kim, B. S.; Cho, H. H. Enhancement of Pool Boiling Heat Transfer Using Aligned Silicon Nanowire Arrays. *ACS Appl. Mater. Interfaces* 2017, 9, 17595–17602.

(36) Shin, S.; Choi, G.; Gallabandi, B.; Lee, D.; Shim, D. I.; Kim, B. S.; Kim, K. M.; Cho, H. H. Enhanced Boiling Heat Transfer using Self-Actuated Nanobimorphs. *Nano Lett.* 2018, 18, 6392–6396.

(37) Kong, D.; Kang, M.; Kim, K. Y.; Jang, J.; Cho, J.; In, J. B.; Lee, H. Hierarchically structured laser-induced graphene for enhanced boiling on flexible substrates. *ACS Appl. Materials Interfaces* 2020, 12, 37284–37292.

(38) Liu, B.; Liu, J.; Zhou, J.; Yuan, B.; Zhang, Y.; Wei, J.; Wang, W. Experimental study of subcooled boiling pool heat transfer and its “hook back” phenomenon on micro/nanostructured surfaces. *Int. Commun. Heat Mass Transfer* 2019, 100, 73–82.

(39) Liu, B.; Cao, Z.; Zhang, Y.; Wu, Z.; Pham, A.; Wang, W.; Yan, Z.; Wei, J.; Sundén, B. Pool boiling heat transfer of N-pentane on micro/nanostructured surfaces. *Langmuir* 2021, 37, 1089–1101.
micro/nanostructured surfaces. Int. J. Therm. Sci. 2018, 130, 386–394.
(52) Može, M.; Senegacnik, M.; Gregoric, P.; Hocevar, M.; Zupec, M.; Golobic, I. Laser-Engineered Microcavity Surfaces with a Nanoscale Superhydrophobic Coating for Extreme Boiling Performance. ACS Appl. Mater. Interfaces 2020, 12, 24419–24431.
(53) Zhou, J.; Liu, B.; Qi, B.; Wei, J.; Mao, H. Experimental investigations of bubble behaviors and heat transfer performance on micro/nanostructure surfaces. Int. J. Therm. Sci. 2019, 135, 133–147.
(54) Rahman, M. M.; Oleroglu, E.; McCarthy, M. Role of wickability on the critical heat flux of structured superhydrophilic surfaces. Langmuir 2014, 30, 11225–11234.
(55) Cao, Z.; Liu, B.; Preger, C.; Wu, Z.; Zhang, Y.; Wang, X.; Messing, M. E.; Deppert, K.; Wei, J.; Sundén, B. Pool boiling heat transfer of FC-72 on pin-fin silicon surfaces with nanoparticle deposition. Int. J. Heat Mass Transfer 2018, 126, 1019–1033.
(56) Preger, C.; Overgaard, N. C.; Messing, M. E.; Magnusson, M. H. Predicting the deposition spot radius and the nanoparticle concentration distribution in an electrostatic precipitator. Aerosol Sci. Tech. 2020, 54, 718–728.
(57) Yazdchi, K.; Srivastava, S.; Luding, S. Microstructural effects on the permeability of periodic fibrous porous media. Int. J. Multiphase Flow 2011, 37, 956–966.
(58) Xu, J.; Gan, Y.; Zhang, D.; Li, X. Microscale boiling heat transfer in a micro-timescale at high heat fluxes. J. Micromech. Microeng. 2005, 15, 362–376.
(59) Wei, J. J.; Honda, H. Effects of fin geometry on boiling heat transfer from silicon chips with micro-pin-fins immersed in FC-72. Int. J. Heat Mass Transfer 2003, 46, 4059–4070.
(60) Kong, X.; Zhang, Y.; Wei, J. Experimental study of pool boiling heat transfer on novel bistructured surfaces based on micro-pin-finned structure. Exp. Therm. Fluid Sci. 2018, 91, 9–19.
(61) Kim, J. H.; Rainey, K. N.; You, S. M.; Pak, J. Y. Mechanism of Nucleate Boiling Heat Transfer Enhancement From Microporous Surfaces in Saturated FC-72. J. Heat Transfer 2002, 124, 500.
(62) Mikic, B. B.; Rohsenow, W. M. A new correlation of pool-boiling data including the effect of heating surface characteristics. J. Heat Transfer 1969, 91, 245–250.
(63) Haider, S. I.; Webb, R. L. A transient micro-convection model of nucleate pool boiling. Int. J. Heat Mass Transfer 1997, 40, 3675–3688.
(64) Mikic, B. B.; Rohsenow, W. M.; Griffith, P. On bubble growth rates. Int. J. Heat Mass Transfer 1970, 13, 657–666.
(65) Jo, H.; Ahn, H. S.; Kang, S.; Kim, M. H. A study of nucleate boiling heat transfer on hydrophilic, hydrophobic and heterogeneous wetting surfaces. Int. J. Heat Mass Transfer 2011, 54, 5643–5652.
(66) Allred, T. P.; Weibel, J. A.; Garimella, S. V. The petal effect of parahydrophobic surfaces offers low receding contact angles that promote effective boiling. Int. J. Heat Mass Transfer 2019, 135, 403–412.
(67) Jakob, M. Heat Transfer; John Wiley & Sons, 1949.
(68) Zuber, N. Hydrodynamic Aspects of Boiling Heat Transfer. Doctor Dissertation, University of California: Los Angeles, California, 1959.
(69) Haramura, Y.; Katto, Y. A new hydrodynamic model of critical heat flux, applicable widely to both pool and forced convection boiling on submerged bodies in saturated liquids. Int. J. Heat Mass Transfer 1983, 26, 389–399.
(70) Yagov, V. V. Is a crisis in pool boiling actually a hydrodynamic phenomenon? Int. J. Heat Mass Transfer 2014, 73, 265–273.
(71) Kandlikar, S. G. A Theoretical Model to Predict Pool Boiling CHF Incorporating Effects of Contact Angle and Orientation. J. Heat Transfer 2001, 123, 1071.
(72) Ahn, H. S.; Lee, C.; Kim, J.; Kim, M. H. The effect of capillary wicking action of micro/nano structures on pool boiling critical heat flux. Int. J. Heat Mass Transfer 2012, 55, 89–92.
(73) Manetti, L. L.; Ribatski, G.; de Souza, R. R.; Cardoso, E. M. Pool boiling heat transfer of HFE-7100 on metal foams. Exp. Therm. Fluid Sci. 2020, 113, No. 110025.