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Recent Advancements in Flow Boiling Enhancement Using Enhanced Microchannels: A Comprehensive Review from a Fabrication Perspective

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ABSTRACT

The demand for efficient cooling methods for electronic devices, nuclear reactors, satellites, and other high-heat-flux applications has led to the emergence of microchannels as highly effective cooling passages. Microchannels offer a combination of high heat transfer coefficients and compact size, making them ideal for such applications. However, traditional microchannels face challenges like high wall superheat boiling, flow instability, and low critical heat flux values during flow boiling, covering different types of enhanced microchannels, including flow disruption structures, reentrant cavity structures, porous structures, and nanostructures, and evaluating their flow boiling enhancement performance. Highlighting the typical fabrication methods employed for creating enhanced microchannels, such as etching, micro-mechanical cutting, micro electrical discharge machining, chemical vapor deposition, and 3D printing. The advantages and disadvantages of each fabrication technique are discussed to provide valuable insights for researchers and engineers working on microchannel heat sinks. The paper also identifies challenges and outlines future research directions for enhanced microchannels, crucial for their practical application and commercialization in high-heat-flux dissipation systems. By shedding light on the latest developments in flow boiling enhancement through enhanced microchannels, this review aims to pave the way for safer and more efficient cooling solutions in various industries, including microelectronics, defense, solar, and medical components.

1. INTRODUCTION

In our modern world, a wide range of devices is utilized to serve human needs, and the efficient removal of heat from these devices is critical to prevent failures and ensure optimal performance. Boiling has proven to be an effective cooling method, particularly for high-power electronic cooling, avionics systems, satellites, and medical devices. Flow boiling, with its high two-phase heat transfer coefficient, ensures uniform wall temperature along the channel, making it an ideal choice for cooling applications. The advantages of flow boiling are further complemented by the inherent benefits of microchannels, including their compact size, minimal coolant requirement, and high surface-to-volume ratio. As a result, flow boiling in microchannels has become a prominent and reliable cooling method for both single-phase and two-phase flow applications.

However, despite the importance of two-phase flow in microchannels, it faces some fundamental challenges that have driven researchers to seek solutions. Issues such as flow instability, low critical heat flux, and high-pressure drop during flow boiling in microchannels are crucial problems that need to be addressed [1]. Understanding the basic principles of boiling in microchannels is essential [2, 3], and appropriate enhancements and materials must be considered to maintain the significance of microchannels as a preferred cooling method over other techniques.

Flow boiling in microchannels is a promising thermal management technique for high heat flux applications due to its ability to dissipate large amounts of heat with minimal coolant usage. However, the microscale dimensions of these channels introduce unique challenges that are not typically encountered in conventional macroscale systems. These challenges stem from the dominance of surface tension, viscous forces, and capillary effects, which significantly alter the flow and heat transfer characteristics [4]. This paper aims to provide a comprehensive overview of the fundamental issues and challenges associated with flow boiling in microchannels, supported by recent research findings.

Microchannel enhancements can be broadly categorized into active and passive methods, with a preference for passive improvements due to their simplicity and reliability compared to dynamic or smart surfaces that involve more complex manufacturing changes. One of the earliest breakthroughs in microchannels was the pioneering study by Tuckerman and Pease, who experimentally investigated forced convection using silicon microchannel heat sinks to achieve compact size and high heat transfer coefficients [5]. Subsequently, numerous researchers have delved into various parameters to comprehensively address microchannel-related issues [6-10]. Notably, there has been a significant interest in enhancing two-phase flow in microchannels [11, 12], with many studies simultaneously exploring different methods to tackle the high-pressure drop issue accompanying such flow [13].

Numerous review works have provided detailed insights into surface structure enhancements for improved boiling heat transfer. Liang and Mudawar [14] listed nanoscale enhancing techniques, including the use of nanofluids and nanoscale structures for pool and flow boiling, studying their effects on heat transfer and critical heat flux. Liang and Mudawar [15] further specialized in flow boiling heat transfer enhancements, encompassing macro scale, micro, nano, and multi-enhancement techniques.

Kim et al. [16] focused their review on micro- and nano-structured surfaces to improve flow boiling heat transfer, summarizing different fabricated methods in a table to achieve desirable increases in efficiency. Additionally, another review by Deng et al. [17] categorized and summarized enhancement methods in two-phase flow within microchannels, including obstruction flow, cavities, and porous nanostructures. They provided detailed insights into the manufacturing methods, presenting the features and drawbacks of each approach.

1.1 Fundamental issues in flow boiling in microchannels

1.1.1 Flow instabilities

Flow boiling in microchannels is often plagued by flow instabilities, which manifest as pressure drop oscillations, flow maldistribution, and flow reversal. These instabilities arise due to the interaction between the vapor and liquid phases, particularly in confined spaces. Recent studies by Kuo et al. [18] and Wu et al. [19] have highlighted that flow instabilities can lead to premature CHF and non-uniform heat transfer, significantly degrading the thermal performance of microchannel heat sinks.

1.1.2 Flow regime transitions

The flow boiling process in microchannels involves complex flow regime transitions, such as bubbly, slug, annular, and mist flows. The rapid transition between these regimes, driven by the high heat flux and small channel dimensions, complicates the prediction of heat transfer coefficients and pressure drops. Whitaker et al. [20] demonstrated that the intermittent nature of slug flow can cause localized dry out, leading to thermal hotspots and reduced heat transfer efficiency.

1.1.3 Heat transfer deterioration

Heat transfer deterioration is a critical issue in microchannel flow boiling, particularly at high heat fluxes. The formation of vapor films and dryout regions can significantly reduce the heat transfer coefficient, leading to elevated wall temperatures. Recent work by Priy et al. [21] emphasized the role of surface wettability and channel geometry in mitigating heat transfer deterioration, suggesting that hydrophobic coatings and structured surfaces can enhance boiling performance.

1.2 Major challenges in conventional microchannels

1.2.1 Premature Critical Heat Flux (CHF)

Conventional microchannels often experience premature CHF due to the rapid nucleation and growth of vapor bubbles, which block the flow path and reduce the effective heat transfer area. Studies by Kandlikar [22] and Das et al. [23] have shown that CHF in microchannels occurs at significantly lower heat fluxes compared to macroscale channels, limiting their applicability in high-power systems.

1.2.2 Flow reversal

Flow reversal, where vapor bubbles push the liquid coolant backward, is a common issue in microchannels. This phenomenon disrupts the flow distribution and exacerbates flow instabilities. Recent research by Xu et al. [24] proposed the use of diverging microchannels and inlet restrictors to suppress flow reversal, demonstrating improved flow stability and heat transfer performance.

1.2.3 Non-uniform temperature distribution

The small dimensions of microchannels make them susceptible to non-uniform temperature distribution, which can lead to thermal stress and mechanical failure. Adio et al. [25] investigated the use of micro pin fins and nanofluids to enhance temperature uniformity, reporting significant improvements in thermal performance.

1.3 Recent advancements and potential solutions

Recent advancements in microchannel design and surface modification have shown promise in addressing the challenges of flow boiling. For instance, the integration of nanostructured surfaces, as explored by Ding et al. [26], has been shown to enhance nucleation site density and improve heat transfer coefficients. Additionally, the use of hybrid microchannel designs, combining parallel and diverging channels, has been proposed to mitigate flow instabilities and improve flow distribution [27].

The aim of this review paper is to consolidate recent documented studies that investigate passive methods for heat transfer enhancement during two phases in microchannel heat sinks, with a specific focus on the vital role of cavities as the primary sites for bubble formation. The paper emphasizes that numerous enhancement techniques, including surface coating, pin fins, and artificial drilling holes, are designed to create favorable conditions for bubble formation by manipulating cavity characteristics such as dimension and quantity. By centering on these passive methods and comprehending the influence of cavities in flow boiling enhancement, the review intends to contribute to the advancement of more efficient and effective cooling solutions applicable in various fields and applications.

2. THE SITE OF INITIATIONS OF THE BOILING NUCLEUS

In the context of flow boiling and pool boiling, the site of initiation for bubble formation is critical to the overall heat transfer process. Most of the heat is extracted from the heated surfaces during the phase change when bubbles form. For bubble nucleation to occur, a suitable location on the heated surface is required, where the temperature rises above the saturation point.

Natural boiling sites are present on the surface and can be represented by features such as scratches, cracks, and gaps. These irregularities on the surface provide nucleation sites for bubbles to form. However, in some cases, the number or size of these natural sites may not be sufficient for continuous and efficient bubble nucleation. In such instances, it becomes necessary to intervene industrially and modify the surface details to make them more suitable in terms of thermal qualities. Hsu [28] developed a nucleation theory for pool heterogeneous boiling, which likely explores the mechanisms and characteristics of bubble nucleation on heterogeneous surfaces. This theory helps in understanding the factors that influence the formation of bubbles at specific sites on the heated surface. Overall, the understanding of boiling nucleation sites and their manipulation is crucial for improving heat transfer efficiency in various applications, and researchers have been working on developing theories and methods to enhance bubble formation and heat transfer in boiling processes.

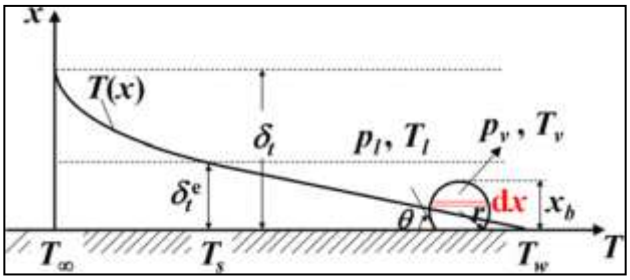


Figure 1. Hsu criteria for bubble formation on the heated surface [28]

In Hsu's nucleation theory for pool heterogeneous boiling, he proposed that a linear temperature distribution exists in the thermal boundary layer adjacent to the heated wall, with a thickness of δ_t. The temperature at a distance X from the wall, T(X), is given by:

$$T(X) - Tl(X) - T\infty = (T\,w - T\infty)(1 - X/\delta_{(t\leqslant)})\ (0 \leqslant X \leqslant \delta\_t) \quad (1)$$

where,

T(X) represents the temperature at a distance X from the heated wall.

Tl(X) represents the temperature of the liquid adjacent to the wall (thermal boundary layer temperature) at a distance X from the wall.

T∞ is the bulk temperature of the liquid (temperature far away from the heated wall).

T w is the temperature of the heated wall.

δ_t is the thickness of the thermal boundary layer.

Hsu further proposed that nucleation occurs when the temperature at the tip of the bubble, Tl(X)b is at least equal to the saturation temperature corresponding to the pressure inside the bubble, Ts(p)v. In other words, nucleation starts when:

$$Tl\ (X\_(b)) \geq Ts\ (P\_(v)) \quad (2)$$

where, (X)b is the projection height of the vapor bubble formed on the heated wall.

To facilitate and optimize the generation of bubbles, researchers have explored modifying the surface morphology to create favorable conditions for bubble formation. By changing the surface details, such as introducing specific features, coatings, or roughness, researchers aim to enhance bubble nucleation and subsequently improve the heat transfer performance in boiling processes. Figure 1 likely shows a schematic representation of the nucleation process, indicating the projection height of the vapor bubble (X)b and the thermal boundary layer adjacent to the heated wall. Understanding the dynamics of bubble nucleation and the role of surface characteristics is essential in designing more efficient heat transfer systems, particularly in microchannel heat sinks, where flow boiling is employed for cooling purposes. The findings from these studies contribute to the development of improved cooling solutions in various applications, including electronics cooling and high-power systems.

3. CREATING ACTIVE CAVITIES IN MICROCHANNEL

Creating active cavities in microchannels is a promising approach to enhancing heat transfer during flow boiling and improving overall cooling performance. Active cavities refer to deliberately designed or engineered features that serve as nucleation sites for bubbles, promoting efficient and controlled boiling in microchannel heat sinks. The nucleation site is a critical parameter in boiling processes, especially in microchannels and other confined geometries. Nucleation is the initial formation of vapor bubbles on the heated surface when it reaches or exceeds the saturation temperature. Creating more active cavities on the heated surface has several significant effects on the boiling heat transfer performance:

•Increased Heat Transfer Area: Active cavities provide additional surfaces for nucleation to occur. By increasing the heat transfer area, more bubbles can form, leading to enhanced heat transfer rates.

•Higher Nucleation Density: More active cavities mean more nucleation sites, leading to a higher density of vapor bubbles. This density increases the overall heat transfer rate as more bubbles participate in the boiling process.

•Lower Wall Superheats: Active cavities lower the wall superheat required for bubble formation. Wall superheat refers to the temperature difference between the heated surface and the saturation temperature. When the wall superheat is reduced, boiling can occur at lower temperatures, making the system more energy-efficient.

•Improved Boiling Heat Transfer Performance: The combined effects of increased heat transfer area, higher nucleation density, and lower wall superheats result in improved overall boiling heat transfer performance. This is particularly beneficial in high-heat-flux applications where efficient cooling is essential.

•Reduced Two-Phase Flow Instability: By promoting earlier and more uniform nucleation, the presence of active cavities can help reduce the occurrence of flow instabilities in two-phase flow systems. Flow instabilities can lead to flow reversal and other undesirable flow patterns, affecting the overall performance of the system.

Researchers in the field of boiling and heat transfer continually explore ways to optimize nucleation and bubble dynamics to improve heat transfer efficiency. Active cavities represent one of the strategies to achieve this optimization, and their design and arrangement play a crucial role in enhancing boiling heat transfer in various microscale applications. Understanding the nucleation behavior and its relationship with active cavities is essential for developing more efficient and reliable thermal management solutions in miniaturized devices. Several approaches have been explored to create such active cavities in microchannels. Some of these approaches include:

3.1 Microcavities or micropores

Fabricating microcavities or micropores on the surface can act as nucleation sites, inducing the formation of bubbles and active cavities during flow boiling. The nucleation site is a crucial parameter that researchers often focus on when studying boiling phenomena [29-33]. Nucleation is the process by which vapor bubbles form on a heated surface when it reaches or exceeds the saturation temperature. The presence and distribution of nucleation sites on the heated surface play a crucial role in determining the efficiency and performance of boiling processes.

Classification of Cavities:

Cavities in boiling research can be categorized into several types, including:

•Reentrant Cavities: Cavities with a three-dimensional shape that extends into the heated surface, promoting bubble nucleation.

•Flow Passage Cavities: Cavities that serve as channels or pathways for fluid flow, affecting bubble formation and behavior.

•Scratches and Cracks: Surface irregularities or defects that can act as nucleation sites during boiling.

•Artificial Nucleation Sites: Purposefully created cavities or engineered features on the bottom surface of the microchannel to control bubble nucleation and enhance boiling performance.

Hsu's theory, as proposed by Hsu [28], provides insights into the preferred dimension of cavities based on the wall superheat for boiling processes. Wall superheat refers to the temperature difference between the heated surface and the saturation temperature of the working fluid. The theory aims to optimize the size of cavities to achieve efficient boiling performance, particularly by promoting early and abundant bubble nucleation. Initially, Hsu's theory was developed for pool boiling. Pool boiling refers to the boiling process that occurs on a heated surface in a pool of liquid. However, researchers have found that the principles outlined in Hsu's theory are applicable not only for pool boiling but also for flow boiling in both conventional-sized channels [34] and microchannels [35]. Researchers consider various parameters related to cavities in the context of boiling and heat transfer processes. These parameters are essential for understanding the behavior of nucleation sites and optimizing boiling performance. Some of the key parameters include:

•Configuration: The overall shape and arrangement of the cavities on the heated surface.

•Dimensions: The size (length, width, depth) of the cavities, which can influence the number and behavior of nucleation sites.

•Shape: The specific geometry of the cavities, including their cross-section and surface characteristics.

•Cavity Distribution: The spatial distribution of cavities on the heated surface affects the uniformity of bubble nucleation and heat transfer.

The study conducted by Kandlikar et al. [35] is a noteworthy example of experimental research where artificial cavities were drilled at the bottom surface of a microchannel to improve boiling efficiency (Figure 2). The researchers focused on flow boiling in a parallel microchannel with a hydraulic diameter (dh) of 332 μm, using water as the coolant. The purpose of the experiment was to investigate the effects of different improvement methods, including the introduction of artificial cavities, on boiling performance. The researchers drilled different-diameter artificial cavities at the bottom surface of the microchannel. These cavities served as nucleation sites, promoting bubble formation and enhancing boiling heat transfer. In addition to artificial cavities, the researchers used different percentages of inlet restrictor areas. Inlet restrictors are used to control the flow rate and pressure of the coolant entering the microchannel. The combination of nucleation sites provided by the artificial cavities and the 4% area pressure drop elements led to the best results in reducing flow instabilities, particularly reverse flow. The presence of artificial cavities and the specific combination of flow improvement methods resulted in reduced flow instabilities during flow boiling. Flow instabilities, such as reverse flow, can negatively impact boiling efficiency and system performance.

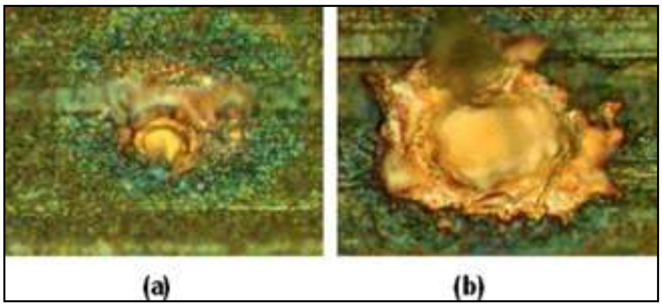
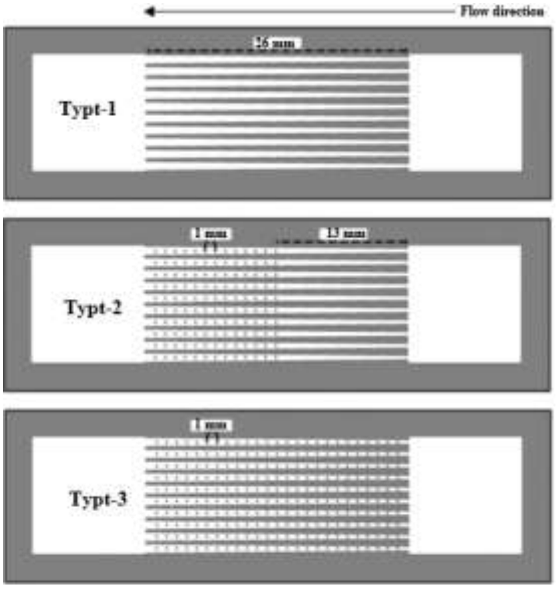


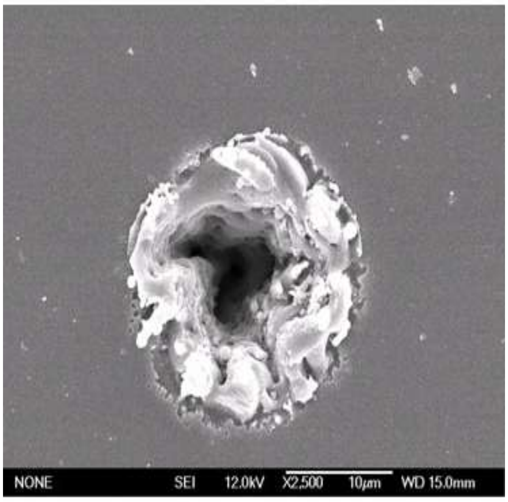
Figure 2. Cavities with different diameters: (a) The small size of 8 μm, (b) Cavities with 22 μm average diam [14]

The study conducted by Lu and Pan [36] represents an innovative approach to control flow instabilities, specifically flow reversal, in microchannels during boiling. Instead of using a microchannel with a uniform cross-sectional area, they employed a divergent microchannel geometry to suppress flow reversal and improve boiling performance. The researchers experimentally investigated three types of divergent cross-sectional microchannels, each with varying numbers and distribution of artificial cavities (Figure 3). By using the divergent microchannel geometry and strategically placing artificial cavities, Lu and Pan demonstrated a successful approach to mitigate flow instabilities and improve boiling performance in microscale systems. The reduced temperature and pressure oscillations are essential for enhancing heat transfer efficiency and preventing adverse effects on the system, such as flow reversal-induced fluctuations.

The nucleation at both the artificial cavities and side walls suggests that the artificial cavities served as efficient nucleation sites, contributing to improved heat transfer rates. The experimental study conducted by Lin et al. [37] focused on flow boiling in a single divergent microchannel with artificial holes organized at the bottom surface (Figure 4). The researchers used a methanol-water mixture as the working fluid. Their aim was to investigate the behavior of nucleation sites and the impact of artificial cavities on boiling performance. The flow visualization showed that nucleation occurred not only at the artificial cavities but also at the side walls of the microchannel. This indicates that the artificial cavities effectively promoted bubble formation, leading to enhanced boiling heat transfer. The results revealed a significant reduction in the wall superheat of the ONB (Onset of Nucleate Boiling) due to the presence of the artificial cavities. ONB refers to the point where boiling nucleation first occurs on the heated surface. The lower wall superheat indicates that boiling was initiated more easily and at lower temperatures with the artificial cavities.



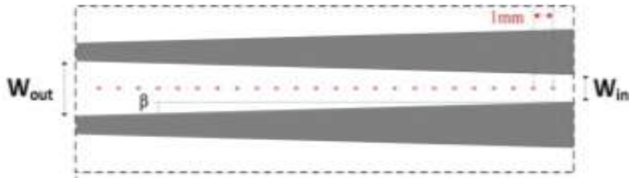
(a)



(b)

Figure 3. (a) Schematic of 3 divergent microchannels, (b) SEM cavity image [36]

The study conducted by Piasecka [38] focused on measuring the temperature distribution in a rectangular channel with micro reentrant cavities. The researchers used a laser drilling technique to create 1-µm deep micro reentrant cavities on the channel surface (Figure 5). They employed the liquid crystal thermal imaging method, using temperature-sensitive liquid crystals, to visualize and analyze the heat transfer behavior within the channel. They created micro reentrant cavities on the channel surface. Reentrant cavities are three-dimensional cavities that extend into the heated surface. These cavities act as nucleation sites for bubble formation during boiling. The enhanced heat flux indicates an improved boiling heat transfer rate due to the nucleation effect of the cavities. They found that boiling incipience occurred earlier on the surfaces with micro reentrant cavities compared to a plain surface without cavities. This indicates that the cavities facilitated bubble nucleation, leading to an earlier onset of boiling. The use of liquid crystal thermal imaging allowed the researchers to visualize the temperature distribution and heat transfer behavior in the microchannel with high spatial resolution, providing valuable insights into the boiling process.



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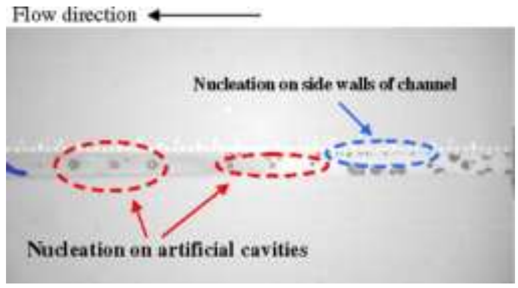
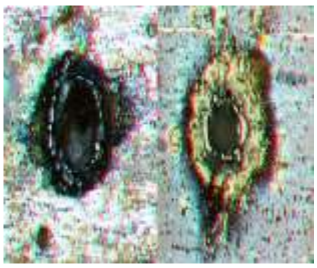
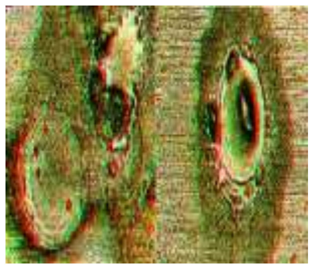


(b)

Figure 4. (a) Schematic of the geometry of the microchannel, (b) High-speed image shows the nucleation at both artificial cavity and wall corner [39]

(a) (b)

Figure 5. (a) 3d photo image of the single micro-recess, (b) 3D topography of the enhanced sampled area with mini-recesses [38]

Zhou et al. [39] focused on investigating the effect of artificial conical cavities on flow boiling heat transfer in a microchannel with a hydraulic diameter of 1.5 mm (Figure 6). The researchers employed artificial conical cavities on the heated surface and visualized the flow to study the boiling behavior. The presence of active artificial conical cavities increased the frequency of the appearance of columnar bubbles during flow boiling. They observed that the average heat transfer coefficients were approximately doubled when using the microchannel with artificial conical cavities compared to a plain surface without cavities. This indicates a significant enhancement in heat transfer performance due to the presence of the cavities.

Wang et al. [40] studied an experimental flow boiling heat transfer performance in three different types of mini channels with a hydraulic diameter of 2 mm (Figure 7). The three types of mini channels differed in their cavity features, including cavity diameter and number. Additionally, the researchers investigated the effect of an electric field on the heat transfer coefficient and flow instability. The presence of cavities provided nucleation sites for bubble formation, while the electric field further improved heat transfer performance by facilitating bubble detachment from the cavities.

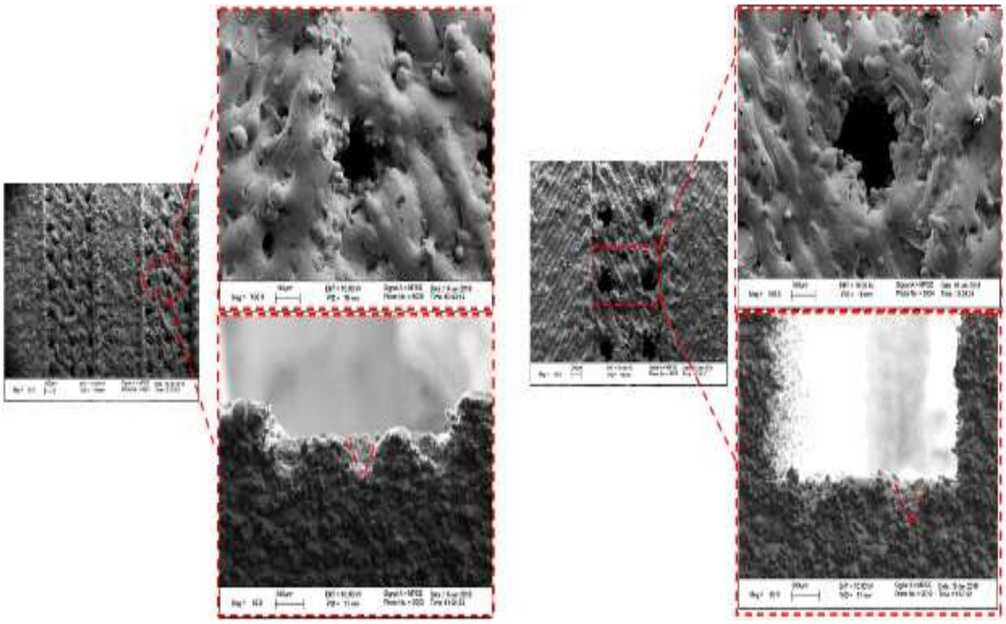


Figure 6. SEM pictures of the heat sink by the direct metal laser sintering [39]

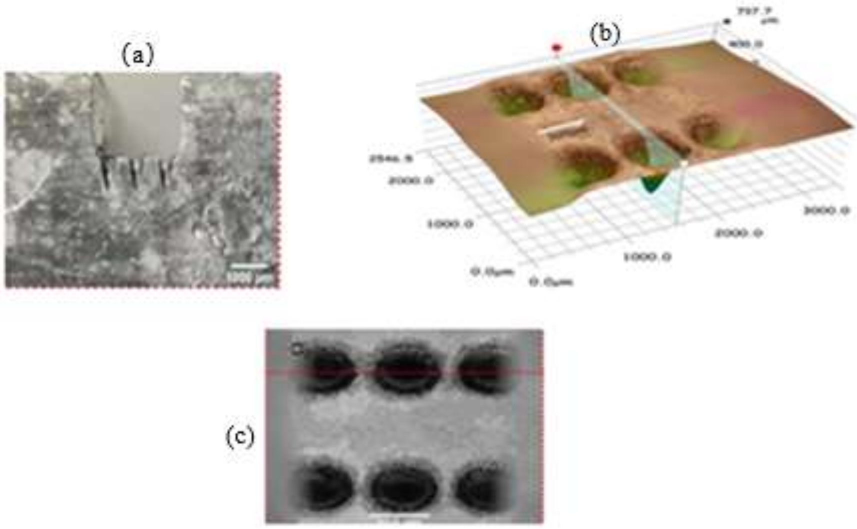


Figure 7. Image represents heat exchanger [41] (a) Side view, (b) Two dimensions, and (c) Artificial cavities using photomicrograph

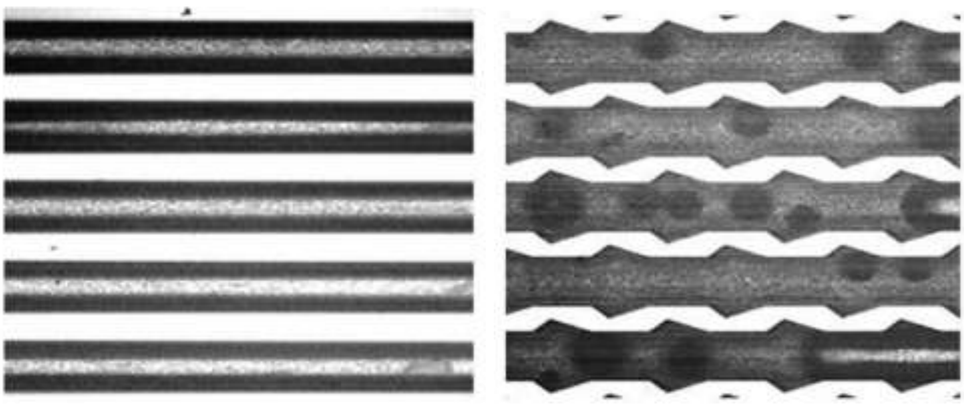


Figure 8. The visualization flow boiling for 20 w/cm^2 heat flux at G = 1 kg/m^2 s in conventional microchannels [42] (a) and (b) enhanced microchannel

Li et al. [42] used two microchannels containing an inlet restriction to reduce flow instability. The first type is a conventional rectangular microchannel. In contrast, the second enhanced microchannel has a triangle shape with 0.05 μm height cavities at each channel side wall (Figure 8). The result shows that the enhanced microchannel has a higher heat transfer coefficient and lower pressure drop. In addition, the axial temperature has more uniformity. The two microchannel types were: Conventional Rectangular Microchannel, which is a common geometry used in microchannel heat exchangers. Inlet restrictions were incorporated to regulate the flow rate and improve flow stability. and Enhanced Triangle-shaped Microchannel with Cavities had a unique triangle shape and featured 0.05 μm height cavities on each side wall. These cavities acted as nucleation sites for bubble formation and contributed to enhancing boiling performance. The study highlights the importance of microchannel geometry and the incorporation of cavities to control flow instability and enhance boiling heat transfer. By utilizing an enhanced triangle-shaped microchannel with cavities, researchers can achieve more efficient and stable boiling performance. The cavities serve as effective nucleation sites, promoting bubble formation and contributing to improved heat transfer rates.

Reentrant cavities are three-dimensional cavities that extend into the heated surface, and they have shown promising potential for improving heat transfer performance in microfluidic systems. The presence of reentrant cavities increases the surface area available for heat exchange, leading to improved heat transfer rates. The three-dimensional cavities may affect fluid flow patterns, pressure drop, and flow uniformity, which are important factors to consider in microscale heat exchangers and cooling systems. Reentrant cavities serve as effective nucleation sites for bubble formation during boiling. As mentioned earlier, they can also act as nucleation sites in single-phase heat transfer, promoting the early formation of vapor bubbles and improving heat transfer efficiency.

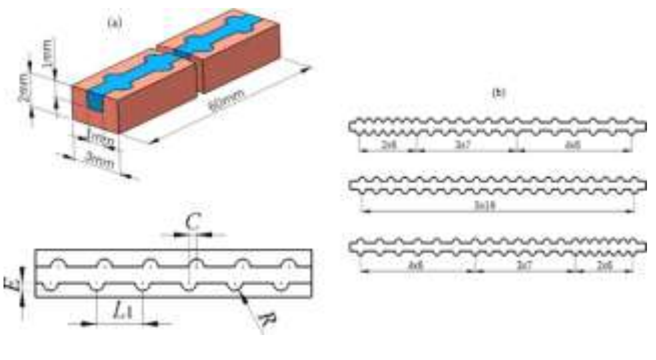
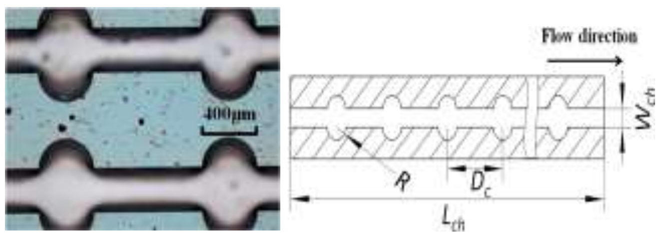


Figure 9. Structural parameters of a microchannel with FSCs and distribution of FSCs in the microchannel: (a) Microchannel with FSC, (b) Distribution of FSCs in a microchannel [41]

Many researchers studied the enhancement of single-phase heat transfer and flow characteristics by comparing the smooth conventional microchannel with reentrant cavities. This comparison helps assess the impact of the cavities on heat transfer enhancement and flow performance. The experimental comparative study conducted by Pan et al. [41] aimed to compare the performance of two types of microscale heat exchangers: A straight microheat exchanger and a fan-shaped reentrant microscale heat exchanger. The researchers visualized the flow patterns and measured heat transfer characteristics to evaluate the differences between the two designs (Figure 9). The heat transfer performance of the structured micro heat exchanger improved as the flow rate of the working fluid increased. Higher flow rates facilitated more efficient heat exchange, leading to increased heat transfer rates in the micro heat exchanger with fan-shaped reentrant cavities. The unique fan-shaped structure influenced fluid flow patterns, creating better flow mixing and enhanced flow turbulence. These enhancements contributed to improved heat transfer efficiency. The study conducted by Liu et al. [43] involved 3-D numerical models to investigate the low Reynolds number flow characteristics and heat transfer in a microchannel with structured fan-shaped cavities (Figure 10). The presence of structured fan-shaped cavities in the microchannel led to an enhancement in convective heat transfer the fluid flow experienced less resistance as it passed through the microchannel with the cavities, resulting in improved flow characteristics.

Figure 10. A schematic display of 3D geometric parameters of a serpentine microchannel with fan-shaped reentrant cavities [43]

The reduction in flow resistance also has practical implications for reducing energy consumption and pressure drop in microfluidic systems. The experimental study conducted by Huang et al. [44] investigated the heat transfer and flow characteristics of four micro-scale heat exchangers. One of the heat exchangers had a conventional shape, while the other three types featured fan-shaped reentrant cavities with different cavity radii, as shown in Figure 11.



(a) (b)

Figure 11. Structure of microchannels with reentrant cavities: (a) Structural parameters microchannel, (b) Test section #4 was observed with a microscope [44]

The researchers used deionized water as the working fluid, which flowed through 10 parallel microchannels with a constant hydraulic diameter of 300 μm for all four types of heat exchangers. The findings suggest that the inclusion of fan-shaped reentrant cavities in micro-scale heat exchangers positively affects heat transfer performance and flow behavior. The study observed that increasing the radius in the fan-shaped reentrant cavities led to a more significant reduction in pressure drop. This indicates that larger cavities provided better flow characteristics, resulting in lower resistance and pressure drop in the microchannels. Hou and Chen [45] compared the performance of three different shapes of reentrant cavities in a microscale heat exchanger, as shown in Figure 12. The researchers aimed to determine which cavity shape provided the most effective heat transfer enhancement in the microscale heat exchanger.

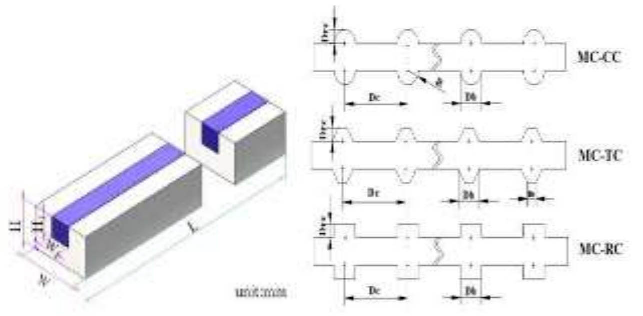


Figure 12. The different types of microchannels [45]

The researchers compared the heat transfer enhancement achieved with each cavity shape. Based on their findings, the circular-shaped reentrant cavities were identified as the most effective in enhancing heat transfer in the microscale heat exchanger. The trapezoidal shape ranked second, and the rectangular shape was found to be less effective in enhancing heat transfer compared to the other two shapes. Reentrant cavities serve as effective nucleation sites for bubble formation during boiling. The three-dimensional nature of these cavities provides additional surface area for bubble initiation, leading to an increased number of nucleation sites. This promotes the formation of vapor bubbles and enhances the heat transfer process. The presence of reentrant cavities facilitates the early onset of boiling incipience, which is the point at which vapor bubbles start to form on the heated surface. Early bubble nucleation reduces the wall superheat required for boiling initiation. While enhanced flow boiling heat transfer is achieved, studies have also shown that reentrant cavities can lead to a reduction in pressure drop. The altered flow characteristics, including improved flow mixing and reduced flow resistance, contribute to lower pressure drop in the microchannel. These cavities can help mitigate flow instabilities and flow reversals, contributing to a more stable and controlled flow behavior.

The experimental study conducted by Kuo and Peles [46] investigated the effect of using a reentrant passage in microchannels on flow boiling instability. They compared three different microchannel types to understand how the presence of reentrant cavities affects flow boiling behavior. The three microchannel types studied were Microchannel with Reentrant Cavity Surface, Microchannel with Interconnected Reentrant Cavity Surface, and Microchannel with Plain Surface. The study highlights that the use of reentrant cavities in microchannels can influence flow boiling instability. While reentrant cavities may enhance heat transfer and flow characteristics in certain scenarios, their presence can also lead to flow instabilities in certain flow conditions. These findings provide valuable information for understanding the complex interactions between cavities, two-phase flow, and heat transfer behavior in microscale heat exchangers and cooling systems. The comparative study conducted by Deng et al. [47] involved two copper microchannel heat sinks, as shown in Figure 13. The first microchannel heat sink was of the conventional type, while the other had uniquely Ω shaped reentrant configurations on the surface. Both microchannel heat sinks had the same hydraulic diameter (Dh).

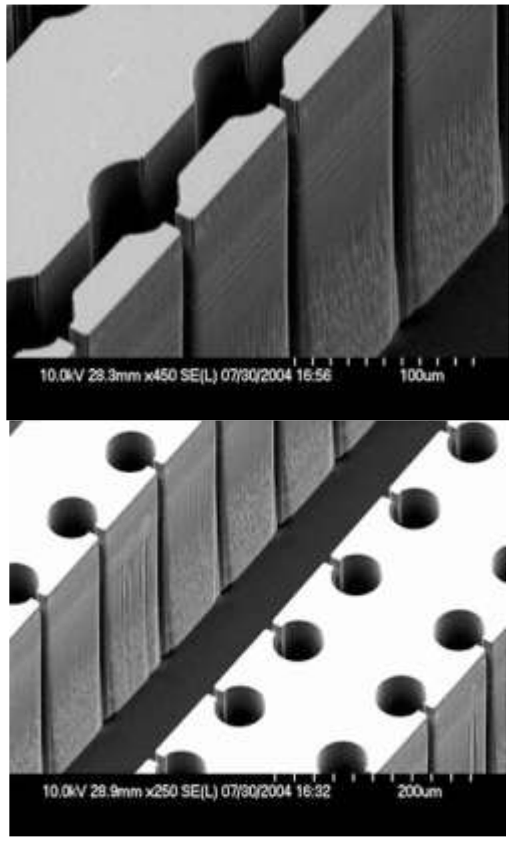


Figure 13. Microchannel with different wall configurations: (a) Interconnected reentrant cavity microchannel, (b) None connected reentrant cavity microchannel [47]

The researchers tested deionized water and ethanol as working fluids and explored different inlet sub-cooling and mass flux conditions. They found that the Ω shaped reentrant microchannel heat sink has potential benefits for flow boiling heat transfer and flow stability. The reentrant configurations on the microchannel surface enhance heat transfer at higher inlet sub-cooling and heat flux conditions, making it a suitable option for demanding cooling applications. Moreover, the reduced pressure drop and improved flow stability in the Ω shaped reentrant micro-channel provide additional advantages in terms of energy efficiency and system reliability. Such microchannel heat sinks with reentrant configurations are promising candidates for applications in electronics cooling, power electronics, and high-performance microfluidic systems. Deng et al. [47] focused on obtaining higher enhancement in heat transfer and flow boiling performance by modifying the reentrant microchannel design. They introduced an interconnected microchannel that incorporated reentrant cavities, as shown in Figure 14.

The modifications aimed to address certain challenges that can arise in microscale passages and further enhance the heat transfer characteristics. They found that the modified design, which combines an interconnected microchannel with reentrant cavities, provides significant advantages over conventional microscale heat exchangers. The reduction in confinement and inlet properties fluctuation, along with the benefits of reentrant cavities, collectively contribute to higher heat transfer enhancement and flow stability. Deng et al. [48]

present an experimental intersection microchannel with an acute angle. This pattern formed pins diamond shape compared with the conventional reentrant microchannel ram using water and ethanol as a working fluid. They found more enhancement in 2-phase heat transfer using water with interconnected microchannels than ethanol.

Also, using (PFIRM) shows lower flow resistance in the 2-phase region and more stable flow. Li et al. [49] studied experimentally the benefit of using the combined cavities and micro nozzle using HFE 7100 as the working fluid. They discuss the boiling physical effect flowing in the microchannel by enhancing the surface. They found a significantly reduced pressure drop by integrating the bypass and removing the confined bubble.

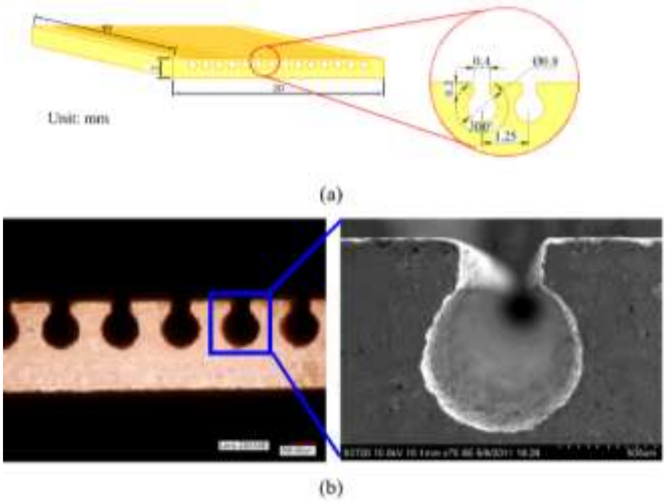


Figure 14. (a) Formal scheme of reentrant cavities sample, (b) Form of side view for reentrant cavities using scanning electron microscope [49]

3.2 Extended surface area

Extended surface area, also known as extended surfaces or fins, refers to a technique used to enhance heat transfer between a solid surface and the surrounding fluid. It involves adding additional surface area to a solid object to increase its heat transfer capacity without significantly increasing its volume. The primary purpose of using extended surfaces is to improve the efficiency of heat transfer processes, such as conduction, convection, and radiation. In micro-scale heat exchangers and micro channel-based cooling systems, enhancing flow boiling performance is crucial for efficient heat transfer and thermal management. Overall, incorporating extended surface area in microchannels for flow boiling provides a practical approach to optimizing thermal performance. Researchers and engineers often explore various configurations and geometries of extended surfaces, fins, and micro-structured surfaces to achieve the desired enhancement in flow boiling heat transfer. The goal is to strike a balance between heat transfer enhancement, flow stability, and pressure drop to meet the specific requirements of the cooling application while maximizing overall system efficiency. The use of extended surface area in microchannels is an essential aspect of modern thermal management solutions for electronics cooling, power generation systems, and other miniaturized heat transfer applications. Flow disruption structures play a significant role in enhancing heat transfer in microchannel heat sinks [50]. These structures are designed to disrupt the normal development of thermal and flow boundary layers, resulting in improved heat transfer performance for the following reasons:

•Disruption of Thermal and Flow Boundary Layers: Flow disruption structures are strategically placed on the inner walls of microchannels to disturb the thermal and flow boundary layers that form near the solid surface. By disrupting these boundary layers, the structures enhance the exchange of heat between the solid surface and the flowing fluid, leading to improved heat transfer efficiency.

•Reduction in Thermal Boundary Layer Thickness: The presence of flow disruption structures reduces the thickness of the thermal boundary layer, which is the region of fluid adjacent to the heated surface where heat transfer occurs primarily by conduction. A thinner thermal boundary layer facilitates more effective heat transfer and increases the overall heat transfer rate.

•Prevention of Bubble Blocking in Boiling Flow: In a two-phase boiling flow, bubbles can form and grow on the heated surface. Flow disruption structures help prevent bubbles from blocking the flow path, ensuring continuous fluid flow and enhancing heat transfer. They create pathways for the bubbles to move away from the heated surface, reducing the likelihood of flow blockage and enhancing heat transfer efficiency.

•Corner Effect for Cavities Nucleation: In some flow disruption structures, such as fins with corners, these corners act as suitable spots for cavities nucleation during boiling. The corners provide nucleation sites for bubble formation, promoting the onset of boiling and enhancing heat transfer performance.

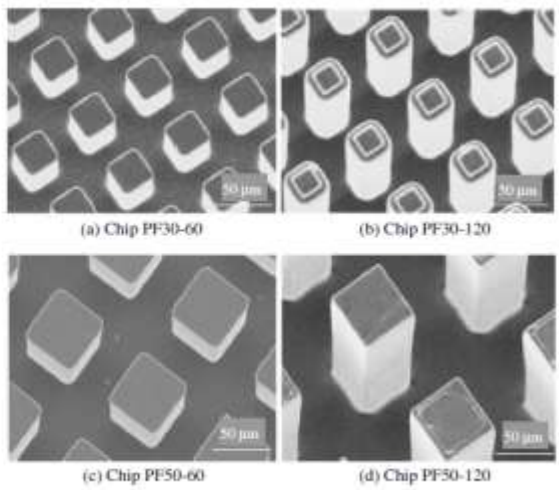


Figure 15. Four samples of chips with different dimensions [51]

The study conducted by Wei et al. [51] investigated the heat transfer characteristics and bubble behavior in microchannels with enhanced surfaces. They used a high-speed camera to study the bubble formation process in the small gap between two adjacent fins, as shown in Figure 15. The objective was to explore the effect of these flow disruption structures on heat transfer and boiling performance compared to a smooth microchannel surface. They found that the presence of a small gap between the adjacent fins in the microchannel provided suitable active cavities for bubble nucleation during boiling. These cavities served as nucleation sites for vapor bubble formation, promoting early boiling incipience. Also, the disruption of thermal and flow boundary layers, as well as the presence of active cavities, contributed to the increased heat transfer efficiency. Ma et al. [52] focused on flow boiling heat transfer in microchannel heat sinks with different chip configurations. They tested five different chips, one of which had a smooth surface (smooth chip), while the other four chips had a structured surface with pin fins. The pin fins had varying heights, but the thickness of the fins remained constant for all the chips. The presence of pin fins on the surface of the chips significantly improved heat transfer during flow boiling. The fins disrupted the thermal and flow boundary layers, leading to enhanced convective heat transfer between the chip surface and the flowing fluid. This improvement in heat transfer was observed across all the chips with structured surfaces compared to the smooth chip. They observed that the chips with structured surfaces, particularly those with pin fins, exhibited an increase in the critical heat flux. The critical heat flux is the maximum heat flux that can be dissipated at the onset of boiling before the surface experiences a significant rise in temperature. By using fins, the researchers were able to achieve higher critical heat flux values, indicating improved boiling performance. The study conducted by Pulvirenti et al. [53] focused on flow boiling heat transfer in a narrow rectangular channel with a vertical position using HFE-7100 as the working fluid under saturation conditions. The researchers compared the performance of an offset fin evaporator with another evaporator that did not have fins. The offset fins evaporator featured a structured fin strip design within the narrow rectangular channel. The presence of offset fins provided additional surface area for heat transfer and disrupted the thermal boundary layer, enhancing convective heat transfer between the heated surface and the flowing fluid. The results showed that the offset fins evaporator outperformed the no fins evaporator, particularly at low heat loads. At lower heat loads, the offset fins facilitated more efficient heat transfer, leading to better cooling performance compared to the evaporator without fins. The experimental study conducted by McNeil et al. [54] focused on flow boiling heat transfer and pressure drop in a test setup with a cross-sectional area of 1 mm^2. The test setup included pin fins, and the researchers used water as the working fluid for their investigations. The use of pin fins and the increased surface area influenced the flow behavior, leading to changes in pressure drop across the test setup. The presence of confined spaces, such as those between pin fins, can impact fluid flow and heat transfer behavior. This confined effect likely contributed to the enhancement of heat transfer and influenced the overall flow characteristics within the test setup. Krishnamurthy and Peles [55] investigate the impact of a line micro pin fin in a rectangular microchannel and its influence on flow boiling heat transfer. They compared this configuration with a plain wall conventional microchannel to understand the heat transfer enhancement achieved through the addition of the line micropin fin. The line micropin fin is a type of extended surface that extends along the length of the microchannel. This configuration is designed to increase the surface area available for heat transfer and disrupt the thermal and flow boundary layers. The enhanced surface area provided by the line micro pin fin improved convective heat transfer between the heated surface and the fluid, leading to higher heat transfer rates compared to the plain wall microchannel. The line micro pin fin had a positive impact on flow boiling heat transfer. It promoted fluid mixing, disrupted the vapor boundary layer, and facilitated better bubble transport, leading to improved heat transfer during flow boiling. Deng et al. [56] studied the impact of micro pin fins with a cone shape arranged in a rectangular microchannel. The objective of their study was to compare the performance of this structured microchannel configuration with that of a traditional smooth rectangular microchannel (Figure 16). The experiments were conducted under subcooled flow boiling conditions, and both water and ethanol were used as the working fluids. The structured microchannel with micro pin fins exhibited more heat transfer enhancement when using ethanol as the working fluid compared to water. The presence of the cone-shaped micropin fins promoted more efficient heat dissipation, allowing the microchannel to handle higher heat fluxes before reaching the critical point. The structured surface disrupted flow patterns and improved fluid mixing, leading to a more stable two-phase flow behavior during flow boiling. The fins provided nucleation sites for bubble formation, promoting early boiling incipience and enhancing overall heat transfer efficiency. The micro pin fins promoted capillary action, enhancing liquid distribution and facilitating more efficient flow boiling. The study introduced by Jung et al. [57] involved conducting a flow boiling experiment to study flow characteristics and two-phase heat transfer using deionized water as the working fluid. The flow boiling experiment was performed in staggered micro pin fin microchannels. The researchers observed that the heat transfer coefficient in the two-phase region decreased with increasing vapor quality. As the vapor quality increases, the flow becomes more dominated by vapor, leading to a reduction in the liquid phase available for heat transfer. This decrease in the liquid phase results in a decrease in the heat transfer coefficient. They found that the pressure drop in the microchannels increased with increasing mass flux. The use of staggered micro pin fins induced a bubbly and slug flow regime during the flow boiling experiment. Bubbly flow refers to the flow pattern characterized by the presence of small bubbles in the liquid, while slug flow involves the periodic formation of elongated gas slugs separated by liquid plugs. A recent survey by Deng et al. [58] examined the new type of open-ring microchannel. They consist of an internal cavity for bubble nucleation and two inner small and outside large rings with separated and converged flow passages. Two unique design configurations of open-ring pin fins, were compared in arrow and overtook. They found that a small wall superheat is required for boiling incipience. The results showed lower pressure drop, better flow stability, and higher heat transfer rate using arrow-type microchannel. Using a high-speed camera, they found the formation of the round area due to the unique shape of the ORPFM, which induces a reduction in the time required for bubble nucleation. Lin et al. [59] examined the enhancement and mechanism of flow boiling heat transfer for three microchannels: smooth microchannel, incorporated micro fins microchannel, and microcavity microchannels. Their results show more enhancement using micro fins due to increasing flow mixing, which promotes the convective heat transfer compared to the microcavity surface. Pranoto et al. [60] presented a comparison between two different kinds of fins that differ geometrically. They tested its effect on boiling heat transfer performance. It was found that the rectangular fins have more cooling performance than the circular shape, which refers to the effect of rectangular corners as effective cavities. Besides, it comprises higher flow resistance than circular fins (Figure 17).

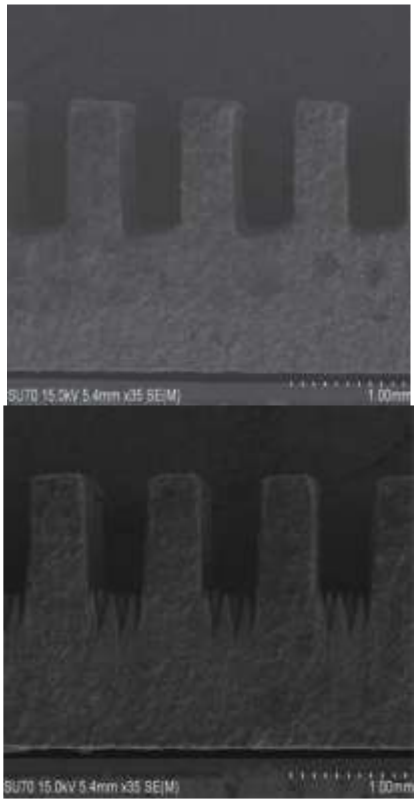


Figure 16. SEM photo of surface: (a) Conventional microchannel, (b) Structured microchannel [56]

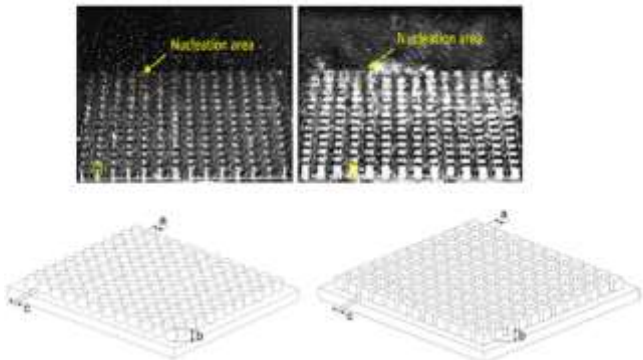


Figure 17. Macro image and surface structure for (a) Nucleate between two adjacent fins, (b) Circular pin fins, (c) Rectangular pin fin [60]

3.3 Activation of new cavities using a surface coating

Surface coating with unique features is another passive enhancement technique used to augment flow boiling heat transfer performance. By applying a coating with specific surface properties, such as roughness or wettability, the contact angle between the heated surface and the working fluid can be altered. This change in contact angle can lead to more active nucleation sites for bubble generation during boiling. The surface coating can be designed to have micro or nano-scale features that create additional cavities or structures on the heated surface. These features can enhance the surface area available for bubble nucleation and promote more efficient bubble formation. The presence of these active nucleation sites reduces the required wall superheat for boiling initiation, resulting in improved heat transfer performance. The alteration of the contact angle also influences the wetting behavior of the working fluid on the heated surface. A coating with a lower contact angle can induce a more non-wetting behavior, creating a Cassie-Baxter state, where the working fluid partially sits on the surface and forms vapor pockets. This enhances the heat transfer performance by reducing the contact area between the liquid and the surface, leading to improved boiling efficiency. Furthermore, the surface coating can promote the formation of thin liquid films or liquid bridges, which can improve the contact between the working fluid and the heated surface. This improved contact enhances the convective heat transfer during flow boiling. Li et al. [61] identified that the increased pressure drop in single-phase flow in microchannels near the wall is primarily influenced by the wettability effect. The wettability of the heated surface, also known as the contact angle between the working fluid and the solid surface, plays a crucial role in determining the fluid flow behavior and heat transfer characteristics. When the surface is hydrophilic, meaning it has a low contact angle and a strong affinity for the working fluid, the fluid wets the surface, and a thin liquid film forms near the wall. This thin liquid film causes a drag force that contributes to the pressure drop along the microchannel. As a result, the pressure near the wall is higher than that in the bulk fluid. On the other hand, if the surface is hydrophobic, it has a high contact angle, and the working fluid prefers to form droplets rather than spreading as a thin film. In this case, the pressure drop near the wall is lower compared to that in the bulk fluid, as the droplets do not exert significant drag forces. The study conducted by Zhou et al. [62] involved examining three models of microchannels with the same dimensions but different contact angles (Figure 18). The researchers experimentally investigated the impact of surface wettability on two-phase heat transfer performance. They found that a lower contact angle on the heated surface resulted in higher two-phase heat transfer coefficients (HTC) at higher Reynolds numbers. A lower contact angle indicates a more hydrophilic surface with a stronger affinity for the working fluid. They treated the surface to achieve a super-hydrophilic surface. By altering the surface characteristics to become more hydrophilic, the wetting behavior of the working fluid is improved, leading to enhanced heat transfer performance. The treatment of the surface to become super-hydrophilic altered the features of the surface cavities. This treatment made the surface cavities more active, increasing their number and resulting in a higher nucleation rate. Enhanced nucleation means that more bubbles are formed on the surface, leading to more efficient boiling and improved heat transfer. By controlling the surface wettability and treating the surface to be more hydrophilic, researchers can achieve higher two-phase heat transfer coefficients and improve boiling performance. Di Sia et al. [63] in his experimental study investigates the impact of nanocomposite coatings on mini channels' surfaces (Figure 19 and Figure 20). The coatings were designed to change the contact angle characteristics of the surfaces, resulting in three types of surfaces: super hydrophilic, superhydrophobic, and hydrophobic. The study aimed to understand the effect of surface wettability by comparing the performance of the treated surfaces with that of uncoated surfaces. The nanocomposite coatings on the mini channel surfaces altered their wetting properties, leading to different contact angles. A super hydrophilic surface exhibits a very low contact angle, indicating strong wetting by the working fluid. A superhydrophobic surface, on the other hand, has a high contact angle, leading to reduced wetting and water repellency. The hydrophobic surface falls between the two extremes in terms of contact angle. The study found that the superhydrophobic surface was the most effective in enhancing heat transfer performance. The strong wetting properties of this surface reduce the time of bubble formation during boiling. This results in more efficient bubble nucleation and improved heat transfer efficiency. Another advantage of the super hydrophilic surface was its ability to suppress the formation of dry areas during boiling. Dry areas are regions where the working fluid does not make good contact with the heated surface, leading to reduced heat transfer and potential hotspots. The super hydrophilic coating helps prevent the formation of these dry areas, leading to more uniform heat transfer and improved thermal performance. Tan et al. [64] numerically studied the effect of wettability on flow boiling heat transfer in a micro tube under subcooled conditions. They proposed three different contact angle surfaces. They concluded that hydrophilic in bubbly and confined bubble flow and hydrophobic in confined bubble and slug flow have better HTC. Lorenzini and Joshi [65] used 2- models to investigate the effect of surface wettability by changing the surface contact angle. More vapor away from the channel caused a higher HTC in a hydrophobic microchannel. The microporous coating is indeed a simple and effective surface treatment technique for enhancing flow boiling in a microchannel. This surface treatment involves applying a microporous layer or coating on the heated surface of the microchannel. The microporous structure creates a high surface area with numerous small pores or cavities, which play a crucial role in enhancing boiling heat transfer performance [66]. The combination of enhanced bubble formation, activated nucleation sites, and improved wettability contributes to overall heat transfer enhancement in the microchannel. This results in higher heat transfer coefficients and improved thermal performance. Many researchers have extensively studied experimental and theoretical methods of controlling the surface structure by coating the surface to change surface roughness. Surface roughness modification through coatings is a common technique employed to enhance heat transfer in various applications, including microchannel heat exchangers and boiling systems. However, certain limitations must be considered to ensure the effectiveness and reliability of these coatings.

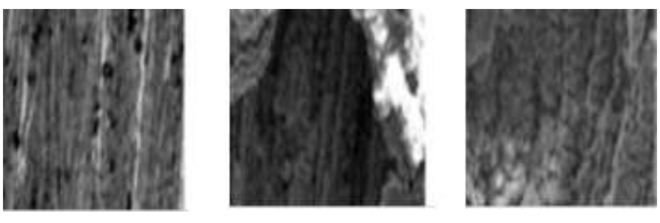


Figure 18. SEM photo of the: (a) Uncoated surface, (b) Hydrophilic structure, (c) Super Hydrophilic structure [62]

Some of the considerations and limitations associated with surface coating for roughness modification as presented below:

•Pressure Drop: Increasing the surface roughness through coatings can lead to an increase in pressure drop within the microchannel or heat exchanger. Higher pressure drop can result in increased pumping power requirements and potential flow instabilities. Researchers need to strike a balance between enhanced heat transfer and acceptable pressure drop levels to ensure efficient operation.

•Cracking and Delamination: Coatings must be applied carefully to avoid cracking or delamination during operation. Cracks or detachment of the coating can lead to reduced effectiveness and may negatively impact heat transfer performance.

•Material Compatibility: The choice of coating material is critical to ensure compatibility with the working fluid and the operating conditions. The coating material should be stable, chemically inert, and resistant to corrosion and degradation.

•Thermal Stability: Coatings must possess sufficient thermal stability to withstand the temperature and heat flux conditions experienced during boiling or heat transfer. High temperatures and rapid heat cycling can potentially degrade or damage the coating, affecting its performance over time.

•Long-term Durability: The durability and longevity of the coating are essential considerations. Coatings should be able to maintain their roughness and heat transfer enhancement properties over extended periods of operation without significant deterioration.

•Fabrication Challenges: The fabrication process of applying the coating should be practical and scalable for industrial applications. Complex or costly coating techniques may limit the widespread adoption of enhanced surfaces.

•Surface Treatment Cost: The cost of surface treatment and coating should be economically viable for the intended application. Cost-effective coating methods are crucial for practical implementation in real-world thermal management systems.

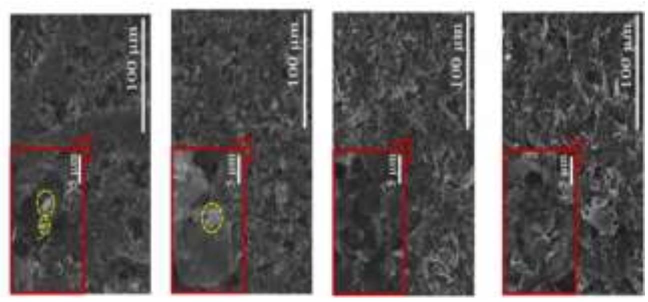


Figure 19. SEM for: (a & b) Super hydrophilic with different coating conditions, (c) Super hydrophobic, (d) Hydrophobic [53]

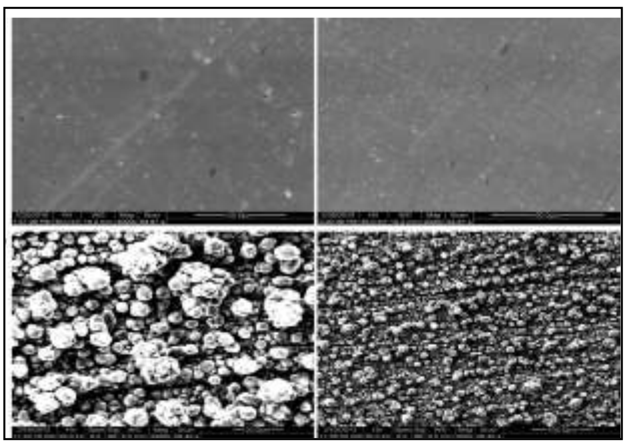


Figure 20. Scanning electron microscopy graphs of: (a) Untreated Cu, (b) $CueAl_2O_3$ treated Cu surface [59]

Bashir et al. [67] and Khan et al. [68] presented a review and critical analysis of the recent developments in micro-Nano scale coating technologies, materials, and their applications for modification of surface geometry and chemistry, which play an essential role in the enhancement of nucleate boiling heat transfer. Morshed et al. [69] used nano coated in the bottom of a single microchannel. They found experimentally heat transfer enhancement in both single-phase and two-phase flow boiling regions compared to conventional smooth microchannels with the same dimensions. Enhancement in the single-phase region was imperceptible, while significantly enhanced in the two-phase region. Bai et al. [70] systematically compare three microchannels of heat sinks coated with different sizes and compare the effect of porous coating by making a comparison with the bar symbol. Using coated cases, they found a lower wall superheat required to initiate boiling. Also, the higher pressure drop with using a coated surface is due to increased surface roughness, as found by Khanikar et al. [71]. Shustova et al. [66] used aluminum oxide as a coating surface on the cover surface of a single microchannel to compare the change in boiling heat transfer behavior with the untreated microchannel. Both types have a very close heat transfer coefficient, while the improvement is evident in increasing the value of heat flux, which causes the boiling crisis to occur. In a recent experimental study, Lee et al. [72] conducted flow boiling heat transfer in a microchannel coated with a porous material. They concluded that a preferable cavity size could be obtained using the coating surface, which induced the bubble formation. Also, a small increment in pressure drop with using coated surfaces.

3.4 Changing surface roughness induced more active cavities

changing the surface roughness can have a significant impact on flow boiling heat transfer in both macro and microscale channel dimensions. Surface morphology, which includes surface roughness and texture, plays a crucial role in influencing the boiling process and heat transfer performance. Jones and Garimella [73] presented that surface roughness changes in the same material when changing manufacturing operating conditions. The influence of surface roughness on flow boiling heat transfer is a complex interplay of fluid dynamics, bubble behavior, and heat exchange mechanisms. Researchers continue to explore innovative surface engineering techniques to tailor roughness patterns for specific applications, such as electronics cooling, microchannel heat exchangers, and other thermal management systems. Jones and Garimella [73] conducted experimental testing of flow boiling heat transfer and flow characteristics using square copper microchannels. The bottom surface of these microchannels was subjected to different structures obtained through various machining processes, as shown in Figure 21. Boiling incipience refers to the onset of boiling and the formation of the first vapor bubbles. In this study, the presence of different surface roughness did not noticeably alter the point at which boiling begins. They also found that a rougher surface resulted in improved heat transfer performance during flow boiling. Also, it was observed that changing the properties of cavities (such as their number and dimensions) due to different surface roughness induced more bubble formation. The presence of surface roughness and modified cavities created more active nucleation sites for bubble formation, leading to increased bubble generation during flow boiling. The study conducted by Jafari et al. [74] involved an experimental investigation of the vapor compression refrigeration cycle (VCRC) with a focus on microheat exchangers (M H.E). They examined the effect of surface roughness on flow boiling heat transfer and pressure drop using three different samples of micro heat exchangers. The surface roughness of the micro heat exchanger led to improved heat transfer performance during flow boiling, where the surface roughness resulted in a higher number of bubble-forming nuclei on the surface than a decrease in surface temperature.

3.5 Fundamental enhancement mechanisms

In summary, researchers have developed various enhancement techniques, including passive methods (e.g., surface modifications, microcavities, fins) and active methods (e.g., electric fields, vibration). These are classified below:

3.5.1 Nucleation site activation

Nucleation sites are critical for bubble formation in flow boiling. The Hsu nucleation theory [28] explains that bubble nucleation occurs when the liquid temperature near a cavity exceeds the saturation temperature. The key mechanisms include:

- Cavity geometry (reentrant, conical, or interconnected) influences bubble nucleation frequency.
- Surface wettability (hydrophilic vs. hydrophobic) affects bubble detachment and rewetting.
- Surface roughness increases nucleation site density by providing more microscopic cavities.

Recent advancements [17, 62] show that engineered microcavities (e.g., Ω-shaped reentrant cavities) enhance nucleation by trapping vapor embryos, reducing wall superheat, and promoting early boiling incipience.

3.5.2 Boundary layer disruption

Flow disruption structures (e.g., fins, ribs, pin fins) enhance heat transfer by:

- Breaking thermal boundary layers, reducing thermal resistance.
- Promoting flow mixing, which improves convective heat transfer.
- Preventing bubble coalescence, reducing flow blockage.

Example: Wei et al. [51] demonstrated that micro-pin fins increase heat transfer coefficients by 30–50% due to enhanced turbulence and bubble detachment.

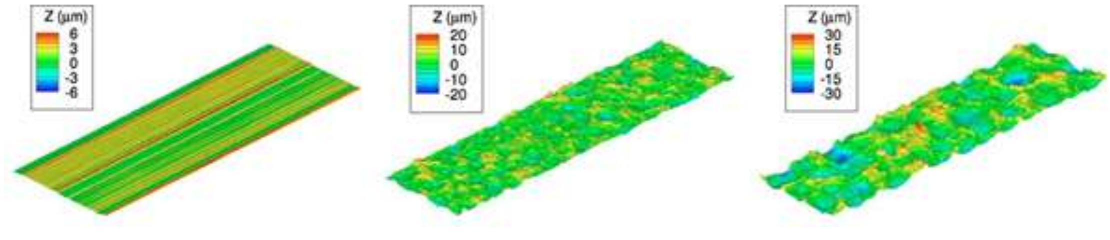


Figure 21. Topographies of 3 models of copper manufactured at different operation conditions [73]

3.5.3 Wettability modification

Surface coatings alter wettability, affecting bubble dynamics:

- Hydrophilic coatings (low contact angle) promote liquid rewetting, delaying dryout.
- Hydrophobic coatings (high contact angle) facilitate bubble nucleation but may increase flow resistance.
- Biphilic surfaces (mixed wettability) optimize both nucleation and rewetting.

Recent studies show super hydrophilic coatings reduce bubble departure diameter, enhancing heat transfer by 20–40% [62, 63].

3.5.4 Porous and nanostructured surfaces

Porous coatings (e.g., sintered metals, nanoparticle layers) enhance boiling by:

- Increasing surface area, improving heat dissipation.
- Providing interconnected vapor pathways, reducing flow resistance.
- Enhancing capillary wicking, sustaining liquid supply to hot spots.

Example: Morshed et al. [69] found that Al_2O_3-coated microchannels delay CHF by 25% due to improved vapor escape pathways.

The effectiveness of flow boiling enhancement in microchannels depends on the interplay between nucleation dynamics, boundary layer disruption, and surface wettability. While microcavities and pin fins improve nucleation and mixing, coatings and porous structures enhance rewetting and CHF. Future advancements should focus on scalable fabrication and adaptive surfaces to overcome existing limitations. This knowledge is crucial for developing next-generation thermal management systems in high-power electronics and energy applications.

3.6 Fabrication techniques for enhanced microchannels

3.6.1 Microcavities and micropores

Purpose: Act as nucleation sites to promote bubble generation.

Techniques and Parameters:

1. Laser Drilling

- Parameters:
- Laser power: 1–50 W.
- Spot size: 10–100 µm.
- Depth: 10–200 µm.
- Advantages:
- High precision (µm-scale cavities).
- Suitable for metals and ceramics.
- Disadvantages:
- Thermal damage to substrates.
- High equipment cost.

2. Chemical Etching

- Parameters:
- Etchants: HF, KOH.
- Etching time: 1–60 min.
- Temperature: 20–80℃.
- Advantages:
- Batch processing capability.
- Low cost.
- Disadvantages:
- Limited to specific materials (Si, Cu).
- Isotropic etching limits feature resolution.

Case Study:

- Deng et al. [23] used Ω-shaped reentrant cavities (hydraulic diameter: 300 µm) to enhance CHF by 40% compared to smooth channels.

3.6.2 Extended surface area (fins/pin fins)

Purpose: Disrupt boundary layers and increase heat transfer area.

Techniques and Parameters:

1. Micro-Pin Fins (3D Printing)

- Parameters:
- Fin height: 50–500 µm.
- Spacing: 100–300 µm.
- Material: Cu, Si, polymers.
- Advantages:
- Customizable geometries (e.g., staggered, conical).
- Enhanced convective heat transfer.
- Disadvantages:
- Increased pressure drop (up to 30%).
- Limited resolution (~50 µm) in 3D printing.

2. Offset Fins (Photolithography)

- Parameters:
- Fin thickness: 20–100 µm.
- Pattern resolution: <10 µm.
- Advantages:
- High reproducibility.
- Improved flow mixing.
- Disadvantages:
- Cleanroom required.
- High fabrication cost.

Case Study:

- Wei et al. [51] achieved a 25% higher heat transfer coefficient using staggered micro-pin fins (200 µm height) in a Cu microchannel.

3.6.3 Surface coatings

Purpose: Modify wettability to control bubble dynamics.

Techniques and Parameters:

1. Hydrophilic Coatings (e.g., SiO_2 Nanoparticles)

- Parameters:
- Coating thickness: 0.1–5 µm.
- Contact angle: <10°.
- Advantages:
- Early boiling incipience.
- Prevents dry-out.
- Disadvantages:
- Delamination at high temperatures.

2. Superhydrophobic Coatings (e.g., Graphene)

- Parameters:
- Contact angle: >150°.
- Advantages:
- Reduced bubble departure size.
- Disadvantages:
- Poor durability under flow shear.

Case Study:

- Zhou et al. [62] reported a 50% higher HTC using superhydrophilic coatings (contact angle: 5°) in Al microchannels.

3.6.4 Surface roughness modifications

Purpose: Increase nucleation site density.

Techniques and Parameters:

1. Laser Texturing

- Parameters:
- Roughness (Ra): 0.1–10 µm.
- Advantages:

- Scalable for industrial use.
- Disadvantages:
- Non-uniform roughness may cause hotspots.
2. Mechanical Abrasion
- Parameters:
- Grit size: 400–2000.
- Advantages:
- Low cost.
- Disadvantages:
- Limited control over feature size.

Case Study:

- Jones and Garimella [73] showed a 20% CHF improvement with laser-textured Cu microchannels (Ra = 2 μm).

To summarize, Fabrication techniques for enhanced microchannels significantly improve flow boiling performance. While microcavities and extended surfaces offer the highest heat transfer gains, surface coatings provide a balance between performance and ease of implementation. Future work should focus on scalable and durable solutions for industrial applications.

4. CONCLUSIONS

The comprehensive review of recent advancements in flow boiling enhancement using enhanced microchannels highlights several critical findings that directly address the challenges and opportunities in this field. The key conclusions drawn from the reviewed studies are as follows:

1. Cavities as Nucleation Sites:

- The introduction of artificial cavities (e.g., microcavities, reentrant cavities, and conical cavities) significantly enhances bubble nucleation, reducing wall superheat and improving heat transfer coefficients. For instance, studies by Kandlikar et al. [13] and Zhou et al. [39] demonstrated that structured cavities doubled heat transfer coefficients compared to plain surfaces.
- Optimal cavity dimensions and distribution are critical. Smaller cavities (e.g., 8 μm) promote early nucleation, while larger cavities (e.g., 22 μm) stabilize flow, mitigating instabilities like flow reversal [13, 38].

2. Extended Surface Area (Fins and Pin Fins):

- Micro pin fins and finned structures disrupt thermal boundary layers, augmenting heat transfer by up to 30%. Rectangular fins outperform circular fins due to corner effects, though they increase flow resistance [49, 51, 60].
- Staggered pin fins induce bubbly/slug flow regimes, enhancing heat transfer at low vapor quality but increasing pressure drop with higher mass flux [57].

3. Surface Coatings and Wettability:

- Superhydrophilic coatings reduce bubble formation time and suppress dryout, improving critical heat flux (CHF) by up to 50% [62, 63]. Hydrophobic coatings excel in confined bubble/slug flow regimes [67].
- Nanoporous coatings (e.g., Cu-Al_2O_3) enhance nucleation site density but may increase pressure drop due to roughness [69, 72].

4. Surface Roughness:

- Roughened surfaces (e.g., machined copper) increase active nucleation sites, boosting heat transfer without altering boiling incipience [73]. However, excessive roughness elevates pressure drop [74].

5. Hybrid and Diverging Microchannel Designs:

- Diverging microchannels with reentrant cavities reduce flow instability and temperature oscillations by 40% compared to uniform channels [38, 43].
- Interconnected microchannels (e.g., Ω-shaped) enhance flow stability and heat transfer at high heat fluxes, particularly with water as the working fluid [51].

6. Fabrication Techniques:

- Laser machining and 3D printing enable complex geometries (e.g., fan-shaped cavities) but face resolution and cost limitations [18]. Chemical etching offers cost-effective batch processing but is material-limited [28, 43].

Future Directions:

- Optimize cavity geometry and coating materials to balance heat transfer enhancement and pressure drop.
- Explore scalable fabrication methods (e.g., hybrid lithography-3D printing) for industrial adoption.
- Investigate nanofluid-coating synergies to further elevate CHF and thermal uniformity.

These findings underscore the potential of enhanced microchannels to revolutionize high-heat-flux cooling systems, provided challenges in fabrication scalability and operational stability are addressed.

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