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THE RECENT TRENDS TO ENHANCE FLOW BOILING IN MICROCHANNEL HEAT SINKS

A. UDAY KUMAR[1]*, N.S. DHANARAJ[2]
[1] Assistant Professor, Dept. of Mechanical Engineering, St.Martin's Engineering College.
[2] Associate Professor, Dept. of Mechanical Engineering, St.Martin's Engineering College.
*Email: draudaykumarme@smec.ac.in

Abstract: A rapid increase in heat flux in various sectors like microelectronics, defense, energy, solar, and medical devices have created an urgent demand for two-phase microchannel heat sinks. These heat sinks are favored due to their compact size, high heat transfer coefficient (HTC), and an excellent heat transfer area-to-volume ratio. However, they face significant challenges in practical applications, including issues like excessive wall temperature leading to nucleate boiling, inherent flow instability, and low critical heat flux in conventional solid parallel microchannels. To address these challenges, substantial efforts have been dedicated to designing and manufacturing improved microchannels to enhance flow boiling in two-phase microchannel heat sinks in recent years. This paper offers a comprehensive overview of recent advancements in enhancing flow boiling and fabricating improved microchannels in this context.

1. Introduction

Heat flux within confined spaces has significantly increased in recent decades because of the aggressive trend toward miniaturization in electronic, defense, energy, solar, and medical components. Examples of devices that have reported maximum heat fluxes of up to 102 W/cm^2 include laser mirrors and densely packed integrated circuits (ICs). The power flux can exceed 103 W/cm^2 in sectors like aviation and very-large-scale integration (VLSI). Furthermore, heat flux removal in the range of 104 W/cm^2 is required for applications like fusion reactors and defense components[1-5]. There is an urgent need for effective cooling techniques because of these serious heat dissipation problems.

To solve problems with high heat flux dissipation in a variety of industries, including the electronics, energy, medical, nuclear, military, and defense sectors, microchannel heat sinks have evolved as a very effective cooling approach. They are used in a variety of products, including catalytic reactors, high-power laser diode arrays, solar cells, fuel cells, refrigeration, cryogenic systems, automotive and aerospace sectors, and more. In comparison to alternative cooling techniques, microchannel heat sinks have a number of significant advantages, including their compact dimensions, high heat transfer area per unit fluid flow volume, low coolant flow rates, and uniform temperature distributions throughout the walls. Since the ground-breaking work of Tuckerman and Pease in 1981 they demonstrate excellent heat dissipation capabilities, with single-phase liquid cooling systems achieving up to 790W/cm^2. Latent heat transfer also allows microchannel heat sinks to effectively disperse heat fluxes up to 1000 W/cm^2 in flow boiling scheme[6-9]. Numerous research endeavors have been dedicated to comprehending the fundamental heat transfer properties and pressure changes in both single-phase convective flow and the two-phase boiling process within microchannel heat sinks. These investigations have been extensively documented in various review articles. Most of the earlier studies primarily concentrated on conventional solid parallel microchannels, including rectangular, triangular, or trapezoidal configurations, during the initial three decades since 1981[2]. To address the challenges associated with conventional microchannels, the utilization of enhanced microchannels with improved heat transfer capabilities represents an ideal solution. Typically, enhancements in heat transfer within microchannel heat sinks can be classified into two main approaches: active and passive methods . Active techniques involve the use of external power sources, such as mechanical mixing, vibration, rotation, suction, injection, or the application of magnetic or electric fields. However, these active methods not only consume external power but also come with high costs and implementation difficulties, which can be limiting factors when applied to compact microchannel heat sinks. Consequently, passive heat transfer enhancement methods have garnered greater attention within the microscale heat transfer community. These methods are generally achieved by altering fluid properties, such as using nanofluids, and/or modifying the heat transfer surfaces.

Therefore, the objective of this review is to provide a concise overview of recent studies concerning heat transfer enhancements within improved microchannels, along with the techniques employed for their fabrication. The primary focus is on evaluating the effectiveness of enhanced microchannels in enhancing flow boiling within microchannel heat sinks. These enhanced microchannel structures are classified into four distinct types based on the various mechanisms used for improving heat transfer: flow disruption structure, reentrant cavity structure, porous structure, and nanostructure.

2. Flow Enhancement Methods

Flow disruption structures improve heat transfer by interrupting the typical development of thermal and flow boundary layers. This reduction in the thickness of the thermal boundary layer prevents bubbles from obstructing the flow in two-phase boiling situations. Over recent years, numerous flow disruption structures have emerged to enhance heat transfer within microchannel heat sinks. Broadly, these structures can be categorized into two types: micro pin fins and interconnected microchannels.

2.1.1. Cross linked microchannels

Interconnected microchannels, known as cross-linked microchannels, play a role in disrupting both the thermal and hydraulic boundary layers by connecting neighboring microchannels. These additional channels introduce lateral fluid transport and mixing, creating alternative pathways for vapor flow during boiling, ultimately enhancing heat transfer. Jiang et al. [9] were among the first to demonstrate that cross-linked microchannels contribute to uniform chip temperature by facilitating even lateral fluid distribution. Xu et al. [10] introduced a silicon microchannel heat sink design featuring parallel longitudinal microchannels and several transverse trapezoidal microchannels. These structures divide the flow length into separate zones, where the thermal boundary layer can be re-established. This re-establishment significantly improved single-phase heat transfer performance while reducing pressure drop compared to conventional microchannel heat sinks. Wang and Ding [11] developed a manifold microchannel heat sink, which consisted of longitudinal microchannels etched into a silicon substrate and transverse microchannels electroplated onto a copper heat spreader. The presence of transverse channels enhanced local heat transfer efficiency through improved thermal flow development. Dang et al. [12] proposed an inclined cross-linked microchannel design, resulting in a 55% improvement in two-phase flow distribution compared to the standard straight channel model, all without an increase in pressure drop.

2.1.2. Pin Fin Microchannel

Micro pin fin structures have the ability to disrupt and redevelop boundary layers, as well as enhance fluid mixing through the formation of vortices. Consequently, they can achieve significant improvements in heat transfer, resulting in a reduction in wall temperature rise. Asadi et.al [15] conducted experimental research on flow boiling heat transfer using square silicon micro pin fins. They observed considerable enhancements in heat transfer compared to a smooth surface, primarily due to the increased surface area and the evaporation of a thin liquid layer between the micro pin fins. Kingston et.al [13] also investigated flow boiling heat transfer and pressure drop in a heat sink featuring square micro pin fins. Their findings indicated that pin-fin surfaces enhance heat transfer by expanding the heat-transfer surface area.

2.1.3. Artificial nucleation cavity structure on the bottom of microchannels

Small cavities have been created at the base of microchannels to serve as artificial nucleation sites. The incorporation of these artificial nucleation cavity structures into microchannels significantly enhances bubble nucleation during the boiling process, leading to improved flow boiling performance. Kandlikar et al. [2] introduced artificial nucleation sites with diameters ranging from 5 to 30 μm at the bottom of rectangular microchannels using a laser drilling process. Their findings indicated that these fabricated nucleation sites, in conjunction with pressure drop elements covering 4% of the area, completely eliminated reverse flow instabilities. Adhama et al. [14] manufactured pyramidal cavities with a square mouth size of 20 μm at the base of parallel silicon microchannels. These cavities initiate nucleate boiling at an earlier stage and promote consistent bubble formation. Additionally, they help eliminate slug flow and significantly reduce instability. Lu and Pan [94] created artificial nucleation sites with diameters ranging from 20 µm to 22 µm in diverging microchannels using a laser-etching process.

Figure 1 Summary of Enhanced microchannels structures and their fabrication method [15] (Deng et.al 2021)

3. Conclusion

According to various improved heat transfer processes, four types of enhanced microchannels—flow disruption structure, reentrant cavity structure, porous structure, and nano structure—can be categorized. The improvement in critical heat flux (CHF), reduction in wall superheat for ONB, mitigation of two-phase flow instability, and enhancement of the boiling flow enhancement of these upgraded microchannels.

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