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State of the art of efficient pumped two-phase flow cooling technologies

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HIGHLIGHTS

- Micro-channels, plate-fin and spray cooling technologies are investigated in detail.
- A review on pumped two-phase flow cooling technologies is presented.
- Heat enhancements for pumped two-phase cooling technologies are discussed.
- Macroscopic, microscopic–nanoscopic and hybrid heat enhancements are presented.

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ABSTRACT

In this paper, different pumped two-phase flow cooling technologies for electronic components are presented. Since electronic components heat dissipation requirements are growing, cooling technologies have evolved from air cooled heat exchanger to technologies involving the use of single or two-phase refrigerants. This review focuses on three technologies that allow dissipation of heat flux over 100 W/cm^2: Micro-channels, plate-fin and spray cooling. Macroscopic, microscopic–nanoscopic and hybrid heat enhancements for all three technologies are also presented.

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Nomenclature

CHF	critical heat flux
CuNWs	copper nanowires
d	diameter
D	depth
DI	deionised
FC	fluoro carbons
H	height
HFE	HydroFluoroEther
HTC	heat transfer coefficient
IRs	inlet restrictors
L	length
Macro	macroscopic
Micro	microscopic
Nano	nanoscopic
PF	performance fluid
PFHE	plate-fin heat exchangers
S	surface
SiNWs	silicon nanowires
W	width

1. Introduction

From the development of the first computer in the 1940 s, effective heat dissipation has played a crucial role in ensuring optimal and reliable operations of electronic devices. The increase of the number of transistors on microchips has led to increases in both power consumption and heat flow. Consequently, the design and reliability of new electronic components are strongly limited by concerns about operating temperature. In this context, electronic cooling technologies have been conceived and improved to keep the temperature of electronic components within acceptable limits for their efficient performance.

Natural convection technology using air was the first cooling system used for removing heat from electronic components. This technology allowed dissipating heat of up to 15 W/cm^2. The use of fans, which increase airspeed, augmented dissipation of these technologies up to 35 W/cm^2 [1,2].

However, as dissipation requirements continued to increase, alternative cooling technologies that use single or two-phase refrigerants were introduced. In these technologies, electronic components are dipped in a refrigerant which removes heat from the component's surface [3]. During this process, the refrigerant can stay liquid or may perform a phase change from liquid to gas. If the phase change occurs, then the process is called pool boiling [4,5]. The amount of heat dissipated with pool boiling technologies can be up to 40 W/cm^2 with dielectric refrigerants [6].

Nonetheless, cooling technologies using air or fluids are not effective enough for removing very large heat fluxes. Nowadays, electronic components need to dissipate heat densities over 100 W/cm^2. To dissipate these densities, heat sinks must be larger than the circuit board containing the electronic components. Besides practical implications, these types of structures would produce both thermal bridges and non-uniform heat flux. This is why several alternatives have been developed to improve heat exchange. They include, as discussed below, pumped two-phase cooling technologies such as micro-channels, plate-fin heat exchangers (PFHE), spray and jet impingement cooling.

To avoid large heat sinks, researchers have developed **micro-channel** technology to dissipate up to 614 W/cm^2 [7]. Micro-channels are integrated onto the circuit board, or in a separate cold plate in contact with it, and allow uniform heat dissipation. A fluid flows through the channels, which are fabricated using a variety of materials such as metal, polymers or silicon. The heat removal can be performed under single-phase flow of liquid or under two-phase flow boiling conditions [8].

PFHE are compact heat exchangers that consist of finned structures inserted between flat plates in a layered disposition where a fluid flows. Diverse finned structure geometries such as plain, wavy, and offset strip fins, can be used depending on the application. PFHE offer both high surface area per unit of volume and high heat transfer effectiveness. This type of structure with only one fluid can be used to manufacture heat sinks capable of removing almost as much heat as micro-channels heat sinks.

The functioning principle for **jet impingement** and **spray cooling** is the same: liquid is injected into a nozzle [3], and the liquid is then finely pulverised either by a strong pressure or by atomisation with air before reaching the surface to be cooled [5]. Both are promising technologies because of their large capacity to remove heat (up to 1200 W/cm^2 [9] for spray cooling and up to 1800 W/cm^2 for jet impingement [5]). The difference between these technologies lies in the speed of the fluid. In jet impingement the fluid is injected at a higher speed which causes erosion on the surface, high pressure losses and a decreasing heat transfer outside a small stagnation point. In spray cooling, the fluid is injected at lower speed than in jet impingement, which allows uniform heat transfer over large surfaces and reduces both erosion and pressure loss [3].

In the literature, there exists no exhaustive review of studies covering several pumped two-phase flow cooling technologies. This paper intends to introduce a comprehensive review of existing works of three pumped two-phase cooling technologies: micro-channel, PFHE and spray cooling. These technologies dissipate heat flux of 100 W/cm^2 or more and use a pumping system to transport fluid to overcome distance limitations. We leave aside jet impingement because of its shortcomings of erosion, and lack of uniform