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Review

Thermal management of microelectronics with electrostatic fluid accelerators

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HIGHLIGHTS

- ► Discuss breakthrough in state-of-the-art of electrostatic fluid accelerators (EFA).
- ► Compare EFAs' performance metrics to those of other airside cooling technologies.
- ► Show analysis of fundamental effect of scaling laws on heat transfer performance.

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ABSTRACT

Optimal thermal management is critical in modern consumer electronics. Typically, a thermal management scheme for an electronic system involves several physical principles. In many cases, it is highly desirable to enhance heat transfer at the solid-air interface while maintaining small size of the thermal management solution. The enhancement of heat transfer at the solid-air interface can be achieved by several physical principles. One principle that is getting increased attention of thermal management design engineers is electrostatic fluid acceleration. This paper discusses recent breakthroughs in state-of-the-art of electrostatic fluid accelerators (EFAs). The paper compares and contrasts EFAs' design and performance metrics to those of other airside cooling technologies used in small form factor applications. Since the energy efficiency, flow rate, and acoustic emissions are highly influenced by the scale of the airside cooling devices, the paper also presents the analysis of fundamental effect of scaling laws on heat transfer performance. The presented review and analysis helps drawing conclusions regarding achievable comparative performance and practicality of using different design approaches and physical principles for different applications.

1. Introduction

1.1. Background

1.1.1. Overview of electronics cooling

For years, the majority of electronic devices relied on conventional rotary fans and heat pipes as a method of thermal management. Although these cooling devices were successful in the past, their application to advanced microelectronics faces several critical challenges due to rapid technology advancement. These technological breakthroughs have resulted in enormous component density and heat flux generation, which limit the amount of available thermal management technologies that thermal engineers can use.

Power delivery components currently occupy up to 30% of the computer's printed circuit board (PCB) area. As thermal engineers continue to reduce the size of the electronic devices, power delivery components will cover more than 30% of the PCB area. The increased component density creates higher heat flux and requires more efficient thermal module for proper functionality. Moreover, it is expected that the anticipated transistor density will be more than 10^{10} per die [1] by 2015. As the CMOS manufacturing processes progress and switch from 90 nm to 16 nm, the predicted power density will grow exponentially by approximately 13 times [1], leading to a dramatic increase in heat flux. This heat flux needs to be transferred elsewhere to maintain lifetime of future microelectronics.

Additionally, skin temperature of consumer electronics becomes critical, especially for smaller form factor consumer electronics, such as smartphones, tablets, and laptops. The skin temperature is the temperature on the external surface of the electronics where

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we touch or hold them. In general, if the skin temperature on consumer electronics is higher than 45°C, long term use of the consumer electronics on human laps or hands will cause increasing skin damage. The skin damage will become worse for small form factor consumer electronics if there is no any proper thermal management solution aiming on this issue.

Furthermore, computer market analysis shows that the global production of small form factor computers has grown approximately 10 times in the past two years [2]. As a result, there is an urgent need for efficient compact thermal modules that ensure functionality of small form factor electronic devices in terms of size, reliability, acoustic level, and heat transport capability; however, the current technology addressing these terms is still not providing needed performance characteristics.

Currently, different kinds of heat transfer technologies can be classified into four categories: airside, heat transporter, active solid-state heat spreader, and passive thermal interface material (TIM), as listed in Table 1.

For airside cooling technologies, the primary conventional thermal management solution for most electronic devices uses both rotary fans and heat sinks. Although heat sinks can passively dissipate lower heat flux for components like low-end graphic processing units (GPU) or dynamic random access memory (DRAM), the heat sink's most significant application is at the heat transfer interface between the heat source and the last step cooling components (rotary fans). In addition, many small form factor electronic devices, such as laptops [3,4,55] and cell phones [4], successfully demonstrate the use of emerging airside cooling technologies like electrostatic fluid accelerators (EFAs), piezoelectric fans, and synthetic jets. EFAs are also known as electrohydrodynamics (EHD) air mover, ionic wind pump, ionic wind engine, corona wind pump, and plasma fan.

Traditional heat transporter cooling solutions, such as heat pipes, liquid, and spray cooling technologies, are designed for higher heat flux applications. Among them, heat pipes are the most common heat transporter cooling solution; they are always used with rotary fans for thermal management of laptops and computer servers. Likewise, vapor chambers and phase change cold plates are derivatives of heat pipes, which provide heat dissipation for even higher heat flux electronic devices.

Table 1
Classification of different operating functions of existing thermal management technologies for cooling of electronics.

Airside	• Rotary fan and heat sink • EFA/EHD • Piezoelectric fan • Synthetic jet
Heat transporter	• Heat pipe • Vapor chamber • Cold plate • Liquid • Spray • Microchannel • Micropump • Droplet manipulation
Active solid-state heat spreader	• Thermoelectric • Thermotunneling • Thermionic
Passive thermal interface material	• Grease: silicone based matrix. • Phase change material: epoxy, polyolefin. • Gel: Al, Al_2O_3 particles in silicone. • Adhesive: Ag particles in a cured epoxy matrix. • Graphene

Emerging heat transporter cooling technologies like microchannels [6–18], micropumps [16,19–21], and droplet manipulation [22] are focused on local high heat flux dissipation and local hot spot cooling applications. Although the industry has used electrospray technology for different applications for couple of decades, the performance and applications for thermal management in electronics is still limited [23–30].

For several decades, thermoelectric (Peltier effect), thermionic, and thermotunneling effects have been used for heat transfer cooling. These devices can be categorized as active solid-state heat spreaders. Heat transfer performance enhancement of these devices has been investigated through various approaches, such as material combination, synthesis processes and figure-of-merit [31,32]. Theoretically, cooling devices based on thermotunneling effect have highest coefficient of performance among these effects; its thermal efficiency is approximately 70% [32].

Passive thermal interface materials (TIM) for heat transfer cooling include greases, phase change materials, gels, adhesives, and graphene. The thermal resistance of a TIM is much lower than that of air, commercial silver epoxy, and metal system [33]. The historical perspective, current status, future development, reliability, and performance degradation of the thermal interface materials have been discussed at length by Prasher [34].

Improving the thermal resistance of current thermal management stacks is critical to enhance heat transfer performance for consumer electronics. Current thermal management stacks for consumer electronics consist of thermal grease, heat pipes, heat sinks, and conventional rotary fans. The analysis shows that the thermal resistance of conventional rotary fans and heat sinks dominates the overall heat transfer performance of current thermal management stacks. In the past, a lot of progress have emphasized on improving heat pipes' and thermal grease's thermal resistance, while the improvement in thermal resistance of conventional rotary fans and heat sinks is limited, because their geometry and structure remains the same.

Additionally, although thermal management solutions have been emphasized on the distinct demands and requirements of the applicable environment, airside cooling technologies remain the preferred choice for thermal management of most consumer electronics, especially for applications on small form factor electronics where thermal management performance of conventional rotary fans degrade as their dimensions are miniaturized (see Section 4.1).

Electrostatic fluid accelerators (EFAs) have the most potential to become critical elements in airside thermal management solutions for advanced microelectronics because they have no mechanical moving parts, have ultra thin and small form factor structure, and can fit in small physical rooms where other mechanical technologies cannot make it. EFAs are highly scalable electrohydrodynamics (EHD)-based solid-state devices that offer silent operation and dynamic enhanced airflow profiles in the boundary layer [35,36]. EHD-based air movement can accelerate bulk airflow [37–40] or disturb the thermal boundary layer close to the solid-fluid interface for heat transfer enhancement [7,41]. Despite the significant developments in the field of EHD over the last half-century [42–45], it has only been in the last decade that research has investigated the direction of micro- and meso-scale EFA cooling applications. Correspondingly, many technological hurdles remain, such as electrode degradation [46–49] and prevention of ozone generation [41,50–63].

This paper reviews potential state-of-the-art airside thermal management technologies, especially EFAs, for small form factor consumer electronics (i.e., notebooks), and compares the heat transfer performance of EFAs to other airside cooling technologies.