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Research Paper

Analysis and feasibility of an evaporative cooling system with diffusion-based sessile droplet evaporation for cooling microprocessors

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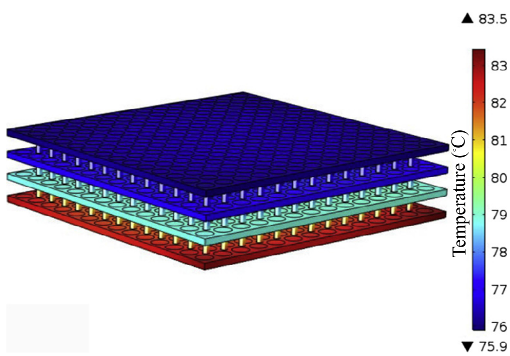
HIGHLIGHTS

- Analytical and numerical modelling of an evaporative cooling system with sessile droplets.
- Cooling for two commercially available microprocessors is investigated.
- Analytical model confirms feasibility of a single layer of droplets.
- Feasibility of tiered system confirmed, with larger and fewer droplets than single layer.
- Analysis yields the minimum number of tiers and posts between tiers required for cooling.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a feasibility analysis is undertaken to assess the capability of an evaporative cooling system using diffusion-based evaporation of sessile water droplets to provide sufficient cooling of microprocessors within the space requirements of the current heat sinks. The study investigates the cooling requirements for the Intel Xenon Processor and the Intel Core i7-900 Processor. An analytical model is developed to determine the capacity of a single layer of water droplets to provide sufficient cooling and calculates the size of the droplets required to meet the cooling needs. It is found that a single layer can provide sufficient cooling for the Xenon Processor with 21,316 droplets having a radius of 0.25 mm and the Core i7-900 Processor with 27,556 droplets having a radius of 0.25 mm. A numerical model is developed to analyze a tiered system that fits within the space restrictions corresponding to the current heat sinks, but can provide the required cooling needs with larger droplets and fewer of them. To decrease the complexity of manufacturing the evaporative cooling system, the numerical model simulated cases to find both (i) the minimum number of posts required to connect each of the tiers and (ii) the minimum number of tiers required to provide sufficient cooling for the microprocessors. The results of the numerical modelling work found that a minimum of 60 posts connecting each of the tiers were required to cool the Xenon Processor and 52 posts for the Core i7-900 Processor. It was also found that a minimum of 3 tiers was required for the Xenon Processor, with a total of 867 droplets having a radius of 2 mm, and 5 tiers required for the Core i7-900 Processor, with a total of 1620 droplets having a radius of 2 mm. The results of the work demonstrate that evaporative cooling systems with diffusion-based evaporation of sessile droplets can provide sufficient cooling for the selected microprocessors, with a number of feasible configurations.

1. Introduction

Evaporating sessile droplets occur in a number of natural and engineered systems [1–5]. In nature, human perspiration is an

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Nomenclature

A_{tot}	total area of substrate (m^2)
A_{exp}	exposed copper surface where there is no droplet (m^2)
$c(T_t)$	saturated water concentration in surrounding air at substrate temperature (kg/m^3)
$c(T_\infty)$	saturated water concentration at ambient temperature (kg/m^3)
D	water vapor diffusivity in air (m^2/s)
H	relative humidity (%)
Δh_{fg}	specific enthalpy of vaporization at interfacial liquid phase temperature (J/kg)
k_{Cu}	thermal conductivity of copper (W/m K)
l_{sp}	distance between post and droplet (m)
l_{sd}	distance between the droplets (m)
$\dot{m}_{ev}$	evaporation rate of droplet (kg/s)
N_d	number of droplets
N_p	number of posts
q_{TDP}	thermal design power for microprocessor (W)
r_p	radius of post (m)
r_d	radius of droplet (m)
T_t	temperature of top surface of substrate (°C)
T_L	temperature at bottom of lowest substrate tier (°C)
T_∞	atmospheric temperature (°C)
$T_{CASE\,MAX}$	maximum temperature for specific thermal design power FOR microprocessor (°C)
$\phi_{isoth}(\theta)$	non-dimensional flow that depends on contact angle (θ)
θ	contact angle (°)

example of evaporating sessile droplets used for thermal management, where sessile sweat droplets evaporate from the skin surface to regulate the body temperature when conduction and convection are insufficient. There is potential to exploit this natural cooling mechanism to develop compact and efficient evaporative cooling systems. For example, a system that mimics human perspiration could potentially replace the current thermal management strategy for microprocessors, which is generally accomplished through forced-air convection with a finned array and a fan. Engineering such a system would require a substrate with a continuously-fed array of evaporating sessile droplets, and several tiers. In order to assess whether or not such a system could remove enough heat to provide adequate thermal management of microprocessors, numerical modelling is applied to simulate the conditions and explore the feasibility.

The evaporation rate of sessile droplets depends on a number of factors, including droplet radius, contact angle, relative humidity, and the diffusion coefficient [6–9]. Numerical modelling can provide a quicker and cheaper approach to analyze the feasibility of a tiered evaporative cooling system with sessile droplets compared to experimental analysis, as well as the capability to explore a number of configurations.

There have been a number of studies on evaporative cooling applications including droplet spray cooling [10], bio-inspired cooling of microelectronics devices using a temperature sensitive hydrogel [11,12], evaporating sessile droplets on a porous membrane inspired by human skin [13], and experimental and theoretical analyses of the evaporation of sessile droplets [6,14–18]. Most of the past work [6,7,9] on evaporating sessile droplets has focused on single droplets, with much of the work on drying droplets [6,7,17], or recent work on a single continuously-fed droplet [14]. The exception is the study by Kokalj et al. [13], in which they developed an analytical model for a single-layered array of evaporating sessile droplets on a porous membrane inspired by human skin, to examine geometrical and environmental parameters on cooling performance. They discovered that increased density of droplets and higher temperatures enhanced the heat dissipation. The focus of the present study is to examine the heat removal capacity of evaporating cooling systems and examine the feasibility for cooling microprocessors. To assess the feasibility of cooling a microprocessor with an evaporative cooling system based loosely on the human perspiration system, a numerical model is required to effectively capture the geometry and temperature distribution of a compact tiered system.

In this study, we first develop an analytical model to simulate an evaporative cooling system with a single layer of sessile droplets. A numerical model is then developed to simulate a tiered evaporative cooling system with arrays of evaporating sessile droplets. We analyze the feasibility of the evaporative cooling system for removing the heat from two types of microprocessors, the Intel Xenon Processor E5-1600/E5-2600/E5-4600 product family and the Intel Core i7-900 Desktop Processor, while maintaining the temperature below the maximum acceptable limit, and confining the system to the same space used by the current heat sinks with forced convection cooling. The feasibility is assessed for the simplest and most conservative case, which is diffusion limited evaporation of sessile droplets. For the Intel Xenon Processor, the simulated configuration consists of a maximum of 4 tiers of substrates with droplet radii of 2 mm and 2.5 mm. For the Intel Core i7-900 Desktop Processor, the simulated configuration consists of a maximum of 13 tiers with droplet radii of 2 mm and 2.5 mm. With this work, we answer the question of whether an evaporative cooling system with evaporating sessile droplets can adequately cool a microprocessor in the same space constraints as existing cooling methods.

2. Analytical model

A simple one-dimensional analytical model is developed to analyze the feasibility of cooling a microprocessor with a single layer of sessile water droplets, using diffusion-based evaporation. The droplet radii used in the simulation are varied from 0.5 to 2.5 mm to provide a range of evaporation rates. For this work, the evaporative cooling system is loosely inspired by the human perspiration system, with sessile water droplets evaporating on a thin copper substrate with a thickness of 2 mm, as shown in Fig. 1, that are assumed to be hemispherical in shape, bounded, and continuously fed from a fluid reservoir beneath them, similar to the continuously fed droplets described in past experimental work [14]. In practice, such a system could have a reservoir machined into the copper substrate while a pressure difference (for example from a gravity fed system) causes the water to flow through small openings and form droplets on the copper surface. Similar to the strat-

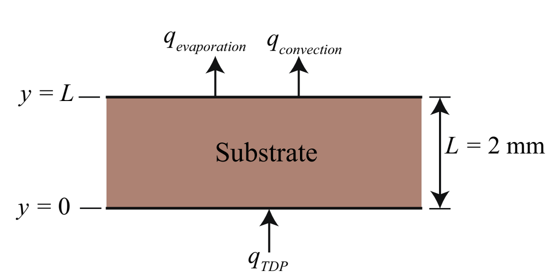

Fig. 1. Schematic of the copper substrate used for the analytical model.