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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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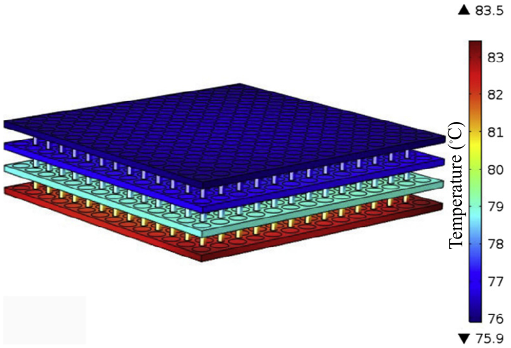
HIGHLIGHTS

- 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.

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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-

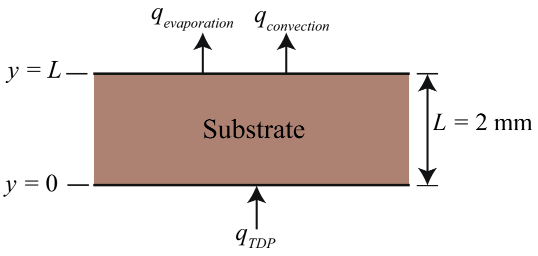

Fig. 1. Schematic of the copper substrate used for the analytical model.

egy employed in a past experimental study for a single droplet [14], small grooves could be machined around each droplet to maintain the spherical shape. The copper substrate is mounted directly on top of the microprocessor, and the boundary conditions include the heat transfer from the microprocessor on the bottom surface, denoted as thermal design power (q_{TDP}), and on the top surface, the heat transfer due to evaporation of the sessile droplets and natural convection from the exposed copper surface, as depicted in Fig. 1. The microprocessor manufacturer provides values for the maximum temperature ($T_{CASE\,MAX}$) corresponding to each value of q_{TDP} [19,20]. The values for $T_{CASE\,MAX}$ obtained from the specifications for the Xenon Processor and Core i7-900 Processor are summarized in Table 1 for the maximum listed q_{TDP} value of 130 W. The copper substrate is assumed to have a thermal conductivity (k_{Cu}) of 401 W/m K [21], exchange heat with the environment at a constant temperature (T_∞) of 25 °C (298 K), and for natural convection from the exposed surface an effective heat transfer coefficient (h) was calculated to be 15 W/m^2 K [21]. The dimensions of the heat sink specified for the Xenon Processor are 91.5 mm × 91.5 mm × 25.5 mm [19] and for the Core i7-900 Desktop Processor are 104 mm × 104 mm × 81.3 mm [20]. For a representative comparison of the evaporative cooling system with the current heat sinks, in the case of the Xenon Processor, we set the copper substrate to have the same length and width (91.5 mm) and limit the height of the tiered configurations to be at or less than 25.5 mm. Similarly, for the Core i7-900 Desktop Processor, we set the copper substrate to have the same length and width (104 mm) and limit the height of the tiered configurations to be at or less than 81.3 mm. The spacing between the droplets was selected as half of the droplet radius to reduce the risk of coalescence and inter droplet interaction [13].

The copper substrate is modelled assuming one-dimensional heat transfer with heat conduction in the y-direction, so the energy equation simplifies to

$$k_{Cu}\left(\frac{d^2T}{dy^2}\right) = 0. \tag{1}$$

At the bottom surface of the copper substrate, $y = 0$, heat is provided from the microprocessor with the following boundary condition

$$-k_{Cu}\left.\frac{dT}{dy}\right|_{y=0} = \frac{q_{TDP}}{A_{tot}}, \tag{2}$$

where A_{tot} refers the total surface area of the substrate. At the top surface of the substrate, $y = L$, there is heat transfer due to the droplet evaporation and natural convection from the exposed copper surface, resulting in the following boundary condition:

$$-k_{Cu}\left.\frac{dT}{dy}\right|_{y=L} = \frac{q_{evaporation}}{A_{tot}} + \frac{q_{convection}}{A_{tot}}, \tag{3}$$

with

$$\frac{q_{evaporation}}{A_{tot}} = \frac{N\dot{m}_{ev}\Delta h_{fg}}{A_{tot}}, \tag{4}$$

$$\frac{q_{convection}}{A_{tot}} = \frac{hA_{\exp}\left[T_t - T_\infty\right]}{A_{tot}}, \tag{5}$$

where N is the total number of sessile droplets, $\dot{m}_{ev}$ is the total evaporation rate of each droplet, T_t is the temperature of the top surface of the substrate, T_L is the temperature of the bottom surface of the substrate, $A_{\exp}$ is the area of the exposed copper surface where there are no water droplets, and the enthalpy of vaporization was obtained from Dash and Garimella [22], where T_t is in K, as:

$$\Delta h_{fg} = 2.7554 \times 10^6 - 3.46T_t^2. \tag{6}$$

Since our modelling domain, shown in Fig. 1, does not include the individual droplets, we do not solve for the interfacial droplet temperature, and therefore calculate the thermal properties using the substrate surface temperature value, T_t, instead.

2.1. Diffusion-based evaporation rate

In this study, we aim to investigate the feasibility for the most conservative case of evaporating sessile droplets, which is evaporation driven only by diffusion. We also neglect the air flow required to remove the vapor evaporating from the droplets, so as not to enhance the convection heat transfer removal and thus consider only the most conservative case. For the evaporation rate, we use an expression developed by Girard et al. [7], for the evaporation of sessile droplets on an isothermal substrate

$$\dot{m}_{ev} = DR\left[c(T_t) - Hc(T_\infty)\right]\phi_{isoth}(\theta) \tag{7}$$

where D is the water vapor diffusivity in air, R is the droplet contact radius, $c(T_t)$ is the saturated water concentration in the surrounding air at the substrate temperature, $c(T_\infty)$ is the saturated water concentration at the ambient temperature, H is the relative humidity, which is assumed to be 44% for this modelling work (the average relative humidity value in our lab), and $\phi_{isoth}(\theta)$ is a non-dimensional flow that depends on the contact angle (θ), which is derived by Hu and Larson [6] to be $0.27(\theta)^2 + 1.30$ for isothermal surfaces. The copper substrate is not isothermal in our analytical model, since it is heated from below by the microprocessor, but a study by Hu et al. [8] showed that for droplets with a contact angle of 90°, the isothermal and non-isothermal [5] expressions have similar results. Since the expression for the isothermal case is simpler, we use it for our modelling work. The temperature dependent diffusion coefficient is as follows [23]:

$$D = D_\infty\left(\frac{T_t}{T_\infty}\right)^2. \tag{8}$$

A polynomial fit expression for the temperature dependent saturated water concentration was developed from the tables given in [21], where T_t is in K, as

$$\begin{aligned} c(T_t) = {} & 9.2 \times 10^{-12}T_t^5 - 1.0965 \times 10^{-8}T_t^4 + 5.406 \times 10^{-6}T_t^3 \\ & - 0.0013987T_t^2 + 0.19268T_t - 11.3968. \end{aligned} \tag{9}$$

The values of the input parameters used in the analytical model are given in Table 1. These parameters are assumed to be constant during the evaporation process.

Table 1
Parameters used in the analytical model for q_{TDP} of 130 W [19–21].

Parameter	Air	Water	Xenon processor	Core i7 processor
Vapor concentration, $c(T_\infty)$ (kg/m^3)		0.0231	–	–
Diffusion coefficient, D_∞ (m^2/s)		2.05×10^{-5}	–	–
$T_{CASE\,MAX}$ (°C)			85.0	67.9
Contact angle, θ (°)		90		
Atmospheric Temperature T_∞ (°C)	25.0			

Table 2
Substrate temperature for the Xenon Processor at 130 W with varying droplet radii for a single layer.

Droplet radius (mm)	Maximum number of droplets[a]	Contact area of droplets (cm^2)	T_L (°C)	$q_{evaporation}$ (W)	$q_{convection}$ (W)	Total evaporation rate (kg/s)
0.25	21,316 (146 × 146)	41.8	70.4	127.2	2.8	5.42×10^{-5}
0.5	5184 (72 × 72)	40.7	86.3	126.0	4.0	5.46×10^{-5}
1	1296 (36 × 36)	40.7	103.6	124.9	5.1	5.52×10^{-5}
1.5	576 (24 × 24)	40.7	114.6	124.2	5.8	5.56×10^{-5}
2	289 (17 × 17)	36.3	126.2	122.8	7.2	5.57×10^{-5}
2.5	196 (14 × 14)	38.5	131.3	122.8	7.2	5.61×10^{-5}

[a] Subject to the substrate area.

Table 3
Substrate temperature for the Core i7-900 Processor at 130 W with varying droplet radii for a single layer.

Droplet radius (mm)	Maximum number of droplets[a]	Contact area of droplets (cm^2)	T_L (°C)	$q_{evaporation}$ (W)	$q_{convection}$ (W)	Total evaporation rate (kg/s)
0.25	27,556 (166 × 166)	54.1	65.1	126.8	3.2	5.37×10^{-5}
0.5	6724 (82 × 82)	52.8	80.2	125.4	4.6	5.40×10^{-5}
1	1681 (41 × 41)	52.8	96.6	124.1	5.9	5.43×10^{-5}
1.5	729 (27 × 27)	51.5	107.8	123.0	7.0	5.46×10^{-5}
2	324 (18 × 18)	40.7	122.1	120.2	9.8	5.43×10^{-5}
2.5	225 (15 × 15)	44.2	126.4	120.3	9.7	5.46×10^{-5}

[a] Subject to the substrate area.

2.2. Analytical model results

The results of the analytical modelling are summarized in Tables 2 and 3 for the Xenon Processor and Core i7-900 Processor respectively. The solutions were generated using MATLAB. The evaporation rate is linearly proportional to the droplet radius, as shown in Eq. (7), thus larger droplets have higher evaporation rates, but the number of droplets that can be placed on the substrate is inversely proportional to the square of the radius, which results in a net increase of the total evaporation rate as the droplet radius is decreased. The higher evaporation rates mean that more energy is removed from the substrate and the temperature decreases as a result, as observed from the modelling results shown in Tables 2 and 3. For the Xenon Processor, a $T_{CASE\ MAX}$ value of 85.0 °C is required at 130 W, which is accomplished with a single layer of 21,316 droplets having a radius of 0.25 mm, as noted in Table 2. For the Core i7-900 Processor, a $T_{CASE\ MAX}$ value of 67.9 °C is required at 130 W, which is accomplished with a single layer of 27,556 droplets having a radius of 0.25 mm, as noted in Table 3. These results show that it is possible to provide sufficient heat removal for these microprocessors using only a single layer of evaporating sessile droplets; however, the number of droplets is quite large, which would make it challenging to manufacture a substrate capable of these numbers of bounded droplets and the holes required to continuously feed the droplets from below. Since the current heat sinks have a height that is larger than a single layer of evaporating droplets, we will now examine the feasibility for multiple tiers of larger droplets to provide the heat removal, which may lead to reduced manufacturing complexity. Due to the complexity of modelling multiple tiers, we develop a numerical model to simulate the cases with more than one layer.

3. Numerical model

The system is modelled as a three-dimensional tiered system, as shown in Fig. 2(a). In order to provide support for the tiers and thermally connect the tiers, a series of posts are required, as seen in Fig. 2(b). In practice, the water that feeds each tier could be fed to the side of each copper substrate layer. The tiered system is aiming to provide sufficient heat removal without requiring the complex high precision manufacturing necessary to produce a single layer with thousands of small droplets that was found from the analytical modelling above. Therefore, droplet radii of 2 mm and 2.5 mm are used in the numerical model, and the

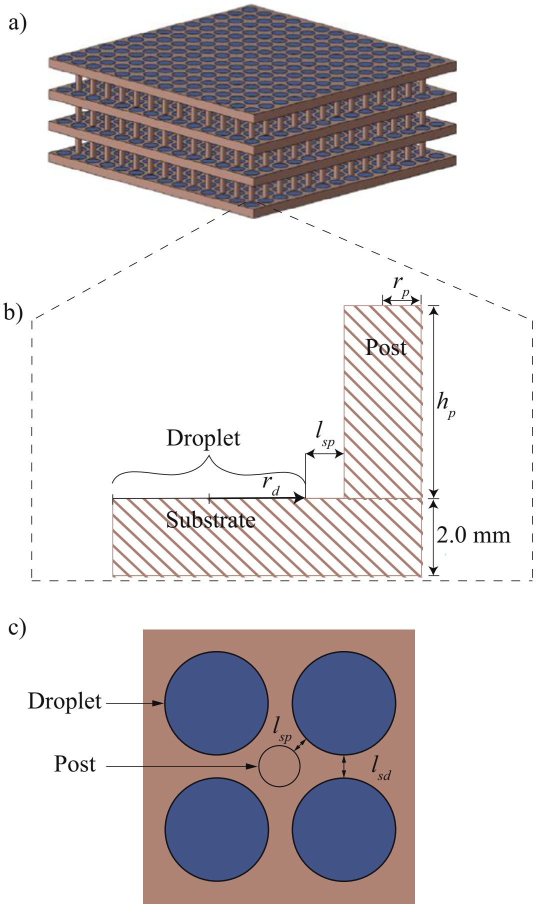

Fig. 2. Schematic of the (a) three-dimensional evaporative cooling system for droplets with a 2.5 mm radius with posts between tiers and 4 tiers, (b) cross-section of a substrate and post showing the dimensions, and (c) overhead view of 4 droplets and a post on the substrate, with spacing dimensions labelled.

Table 4
Geometrical parameters used in the numerical model.

	Xenon processor		Core i7-900 desktop processor	
Parameter	Droplet radius, r_d (2.5 mm)	Droplet radius, r_d (2 mm)	Droplet radius, r_d (2.5 mm)	Droplet radius, r_d (2 mm)
Number of droplets, N_d	196 (14 × 14)	289 (17 × 17)	225 (15 × 15)	324 (18 × 18)
Maximum number of posts, N_p	169 (13 × 13)	256 (16 × 16)	196 (14 × 14)	289 (17 × 17)
Radius of post, r_p (mm)	1	1	1	1
Distance between post and droplet, l_{sp} (mm)	1	0.78	0.80	0.47
Distance between droplet, l_{sd} (mm)	1.25	1	1.25	1
Height of post, h_p (mm)	5	4	5	4

maximum height of the tiers is restricted by the height of the current heat sinks. The model was implemented in COMSOL Multiphysics, which uses the finite element method. Within COMSOL, the heat transfer module was used for the thermal conduction analysis, the mesh was generated using the "physics controlled mesh" option and the element size was set to "extremely fine."

In Fig. 2(b)–(c) the arrangement of posts and droplets is shown along with the corresponding variables for the dimensions, with the values summarized in Table 4. The height of each post (h_p) is set as twice the droplet radius to provide space for the vapor to diffuse and prevent droplet interaction with the substrate layer above it. The maximum number of tiers that can be used for the Xenon Processor are 4 for droplets with radii of 2 mm and 2.5 mm. The maximum number of tiers that can be used for the Core i7-900 Processor are 13 for the droplets with 2 mm radius and 12 for the droplets with 2.5 mm radius.

3.1. Boundary conditions

The heat transfer from the substrate is modelled with similar conditions to the analytical modelled described above, but is implemented in three dimensions. The boundary conditions can be summarized as follows:

1. The posts are made of copper and physically connected to the substrate tiers, resulting in continuous thermal conduction.
2. A constant general inward heat flux ($\dot{q}_{TDP}/A_{total}$) is applied for the bottom of the lowest tier of copper substrate to simulate mounting directly on top of the microprocessors.
3. An outward heat flux ($N\dot{m}_{ev}\,\Delta h_{fg}/A_{drop}$) is applied for each water droplet based on the evaporation rate expression listed as Eq. (7) and dependent on the local substrate temperature.
4. Convective heat flux, with a constant heat transfer coefficient of 15 W/m^2 K for natural convection, is used on all the exposed surfaces of the substrate.
5. The environmental properties of the surrounding air, namely the temperature and relative humidity, are considered to be constant within the tiers throughout the evaporation. In practice, forced convection would be required to remove the vapor and maintain the constant properties, but we do not include forced convection in our model.

4. Results and discussion

The complexity of the tiered evaporative cooling system depends primarily on two variables: the number of tiers and the number of posts. It may be advantageous to reduce either of these variables to generate an evaporative cooling system that is simple to manufacture. Therefore, we model two cases: (i) we determine the lowest number of posts required to provide sufficient cooling with the maximum number of tiers used (limited by the height restrictions imposed by the current heat sink dimensions), and (ii) we determine the lowest number of tiers required to provide sufficient cooling with the maximum number of posts included (one in between each droplet). The modelling is performed for the case of the maximum listed thermal design power of 130 W, as used in the analytical model, and an additional case to assess the feasibility at a lower thermal design power of 80 W. The Xenon Processor and the Core i7-900 Desktop Processor list a $T_{CASE\ MAX}$ value of 74.1 °C and 58.4 °C respectively for a q_{TDP} value of 80 W [19,20].

The relative humidity of the surrounding air is assumed to be constant in our model, in spite of the evaporation introducing vapor into the air and the lack of forced air flow in our system to remove this vapor. In practice, such a system would result in an increasing relative humidity in the surrounding air to the point of saturation, which would cause the evaporation rate to gradually slow to a halt according to Eq. (7). A solution to this would be to use a fan to generate forced air flow and remove the vapor from the space between the tiers. Our model does not include this forced air flow so as not to introduce the complexities of the increased evaporation rate and the enhanced convective heat removal that are functions of the air speed. The case without a fan can be used to demonstrate feasibility, since including the fan in the model would increase both the evaporation rate and the convective heat transfer, resulting in more heat removal from the evaporative cooling system.

4.1. Lowest number of posts with maximum number of tiers

Fig. 3 shows the maximum substrate temperature of the lowest tier (T_L) plotted against the number of posts used to connect each substrate tier. It can be observed that as the number of post increases, the substrate temperature decreases, which is to be expected since the increasing number of posts enables increased thermal conduction between the tiers, resulting in higher temperatures for the upper tiers and increased evaporation rates as a result. From the simulation results in Fig. 3, it can be seen that T_L reached the required value of 85 °C for 130 W with 108 posts for r_d = 2.5 mm and 60 posts for r_d = 2 mm. For a q_{TDP} value of 80 W, the minimum number of posts to reach a T_L of 74.1 °C is 56 posts for r_d = 2.5 mm and 36 posts for r_d = 2 mm. Manufacturing less than 100 posts with 4 tiers (for r_d = 2 mm) may provide a more simple evaporative cooling system than the single layer with thousands of small droplets described in the analytical modelling section above. Notably, for 4 tiers the total number of droplets is 784 for a r_d = 2.5 mm and 1156 for a r_d = 2 mm, which is much less than the 21,316 droplets required for the single layer of r_d = 0.25 mm droplets found for the Xenon Processor in the single layer case.

Fig. 4 shows the variation of T_L versus the number of posts for the Core i7-900 Processor. From the simulation results plotted in Fig. 4, it can be seen that T_L reached the required value of 67.9 °C for 130 W with 60 posts for r_d = 2.5 mm and 52 posts for r_d = 2 mm. For a q_{TDP} value of 80 W, the minimum number of posts to reach a T_L of 58.4 °C is 40 posts for r_d = 2.5 mm and 32 posts for r_d = 2 mm.

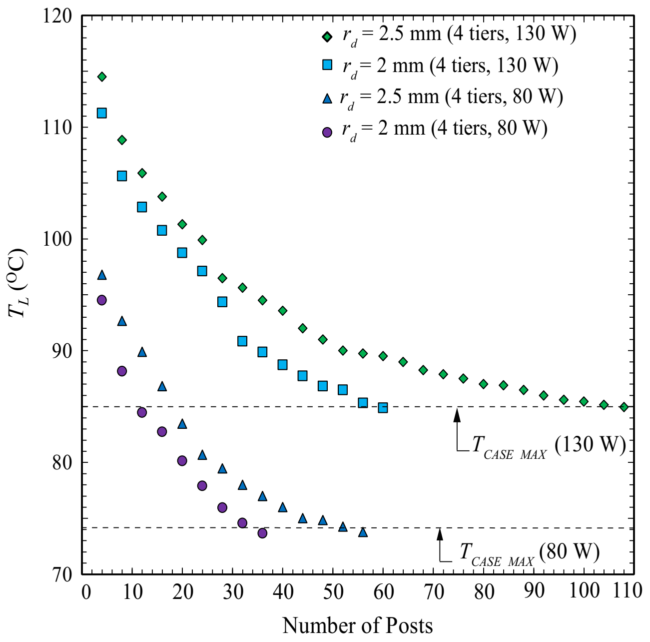

Fig. 3. Maximum value of the substrate temperature in the lowest tier T_L (°C) versus the number of posts connecting each substrate tier for the Xenon Processor with 4 tiers.

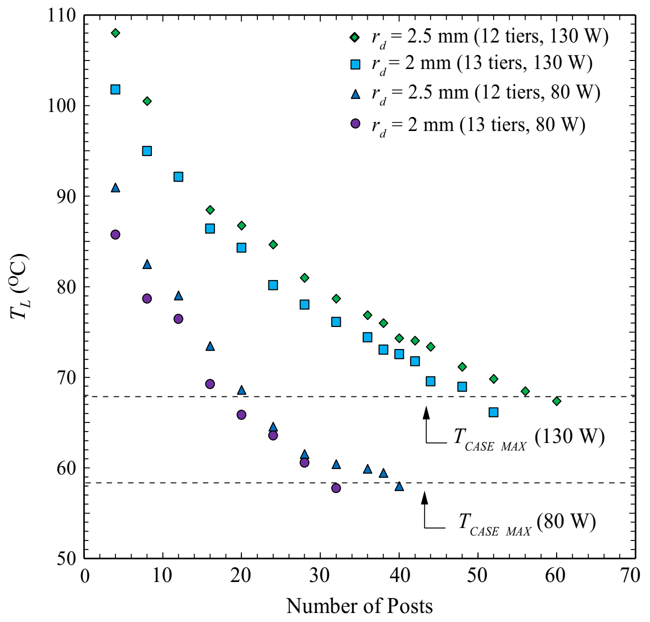

Fig. 4. Maximum value of the substrate temperature in the lowest tier, T_L (°C), versus the number of posts connecting each substrate tier for the Core i7-900 Processor with 12 tiers and 13 tiers.

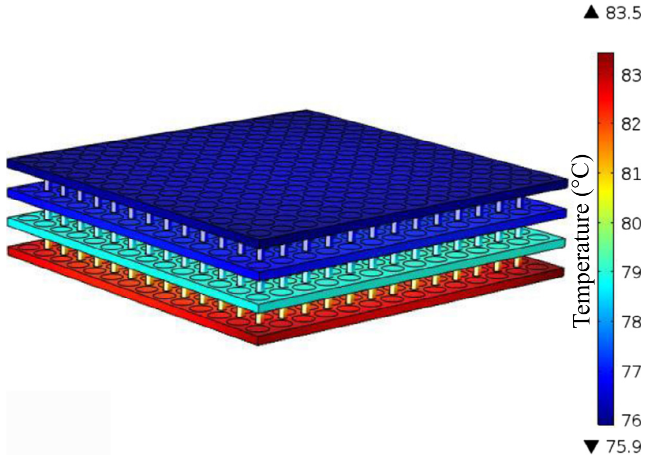

Fig. 5. Temperature distribution for the tiered droplet evaporation cooling system using the maximum number of posts with the minimum number tiers (4) for the Intel Xenon Processor at 130 W with a droplet radius of 2.5 mm.

4.2. Lowest number of tiers with maximum number of posts

The results of the simulations for the minimum number of tiers with the maximum number of posts are summarized in Table 5. For the Xenon Processor, only 4 tiers are required for r_d = 2.5 mm (130 W and 80 W) and 3 tiers are required for r_d = 2 mm case to reach the required substrate temperature. For the Core i7-900 Processor cases with r_d = 2.5 mm, 6 tiers are required for 130 W and 5 tiers are required for 80 W case, and with r_d = 2 mm, 5 tiers are required for 130 W and 4 tiers are required for 80 W. The number of droplets required for the 130 W cases with the Xenon Processor are 784 for r_d = 2.5 mm (4 tiers) and 867 for r_d = 2 mm (3 tiers), and for the Core i7-900 Processor are 1350 for r_d = 2.5 mm (6 tiers) and 1620 for r_d = 2 mm (5 tiers). Reducing the number of tiers can reduce the manufacturing complexity, and there is also a corresponding reduction in the number of droplets required, but there is also a requirement for more posts. So, whether or not the number of tiers should be minimized or the number of posts will depend on the complexity and cost of the specific manufacturing processes. Overall, the feasibility of an evaporative cooling system using evaporating sessile droplets driven by diffusion has been demonstrated for cooling two different microprocessors.

The temperature distribution for the tiered droplet evaporation cooling system is illustrated in Fig. 5 using the maximum number of posts (169) for r_d = 2.5 mm with the minimum number of tiers (4). The temperature can be seen to decrease from the bottom layer to the top layer with a relatively small temperature difference between tiers on account of the maximum number of posts being utilized. The warmest point can also be seen to be the bottom of the lowest tier, which was the reference temperature for this study, T_L, and is the point of contact between the evaporative cooling system and the microprocessor.

Table 5
Minimum number of tiers utilizing with maximum number of posts for different types of microprocessors.

Type of microprocessor (q_{TDP}, W)	Minimum number of tiers (total layer height, mm)		T_L (°C)	
	r_d = 2.5 mm	r_d = 2 mm	r_d = 2.5 mm	r_d = 2 mm
Xenon (130)	4 (25.5)	3 (16)	82.0	85.0
Xenon (80)	4 (25.5)	3 (16)	67.7	71.6
Core i7 (130)	6 (39.5)	5 (28)	64.7	63.7
Core i7 (80)	5 (32.5)	4 (22)	56.0	57.2

5. Conclusions

In this study, both an analytical model and a numerical model were developed to model an evaporative cooling system using an array of evaporating sessile droplets driven by diffusion and assess the feasibility of providing heat removal for two microprocessors, the Intel Xenon Processor and the Intel Core i7-900 Processor. The analytical model demonstrated that a single layer of evaporating sessile droplets is capable of providing sufficient heat removal for both microprocessors with droplets having a relatively low radius and requiring large numbers of them. Specifically, to provide cooling at 130 W for the Xenon Processor, 21,316 droplets were required at r_d = 0.25 mm and for the Core i7-900 Processor, 27,556 droplets were required at r_d = 0.25 mm. The numerical model demonstrated the feasibility of using a tiered evaporative cooling system with larger droplets, with radii of 2 mm and 2.5 mm. The results showed that the tiered system can meet the cooling demand using less droplets and the system can be simplified by either minimizing the number of posts connecting the tiers or minimizing the number of tiers required. With the maximum number of posts between each tier, the number of droplets required for the 130 W cases with the Xenon Processor was 784 for r_d = 2.5 mm (4 tiers), and for the Core i7-900 Processor was 1350 for r_d = 2.5 mm (6 tiers). Overall, the results showed that a single layer and a tiered evaporative cooling system using evaporating sessile droplets driven by diffusion can successfully cool a microprocessor within the current space required for the heat sinks.

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References

[1] K. Sefiane, On the formation of regular patterns from drying droplets and their potential use for bio-medical applications, J. Bionic Eng. 7 (2010) S82–S93.

[2] T. Lim, J. Jeong, J. Chung, J.T. Chung, Evaporation of inkjet printed pico-liter droplet on heated substrates with different thermal conductivity, J. Mech. Sci. Technol. 23 (2009) 1788–1794.

[3] A. Ebrahimi, P. Dak, E. Salm, S. Dash, S.V. Garimella, R. Bashir, M.A. Alam, Nanotextured superhydrophobic electrodes enable detection of attomolar-scale DNA concentration within a droplet by non-faradaic impedance spectroscopy, Lab Chip 13 (2013) 4248–4256.

[4] I.I. Smalyukh, O.V. Zribi, J.C. Butler, O.D. Lavrentovich, G.C. Wong, Structure and dynamics of liquid crystalline pattern formation in drying droplets of DNA, Phys. Rev. Lett. 96 (2006) 177801.

[5] Y.O. Popov, Evaporative deposition patterns: spatial dimensions of the deposit, Phys. Rev. E 71 (2005) 036313.

[6] H. Hu, R.G. Larson, Evaporation of a sessile droplet on a substrate, J. Phys. Chem. B 106 (2002) 1334–1344.

[7] F. Girard, M. Antoni, S. Faure, A. Steinchen, Influence of heating temperature and relative humidity in the evaporation of pinned droplets, Colloids Surf., A 323 (2008) 36–49.

[8] D. Hu, H. Wu, Z. Liu, Effect of liquid–vapor interface area on the evaporation rate of small sessile droplets, Int. J. Therm. Sci. 84 (2014) 300–308.

[9] S. Misyura, Contact angle and droplet evaporation on the smooth and structured wall surface in a wide range of droplet diameters, Appl. Therm. Eng. 113 (2017) 472–480.

[10] J. Kim, Spray cooling heat transfer: the state of the art, Int. J. Heat Fluid Flow 28 (2007) 753–767.

[11] S. Cui, Y. Hu, Z. Huang, C. Ma, L. Yu, X. Hu, Cooling performance of bio-mimic perspiration by temperature-sensitive hydrogel, Int. J. Therm. Sci. 79 (2014) 276–282.

[12] Z. Huang, X. Zhang, M. Zhou, X. Xu, X. Zhang, X. Hu, Bio-inspired passive skin cooling for handheld microelectronics devices, J. Electron. Packag. 134 (2012) 014501.

[13] T. Kokalj, H. Cho, M. Jenko, L. Lee, Biologically inspired porous cooling membrane using arrayed-droplets evaporation, Appl. Phys. Lett. 96 (2010) 163703.

[14] M.A. Mahmud, B.D. MacDonald, Experimental investigation of interfacial energy transport in an evaporating sessile droplet for evaporative cooling applications, Phys. Rev. E 95 (2017) 012609.

[15] Y. Wu, X. Zhang, X. Zhang, M. Munyalo, Modeling and experimental study of vapor phase-diffusion driven sessile drop evaporation, Appl. Therm. Eng. 70 (2014) 560–564.

[16] E. Widjaja, M.T. Harris, Numerical study of vapor phase-diffusion driven sessile drop evaporation, Comput. Chem. Eng. 32 (2008) 2169–2178.

[17] G. Dunn, S. Wilson, B. Duffy, S. David, K. Sefiane, A mathematical model for the evaporation of a thin sessile liquid droplet: comparison between experiment and theory, Colloids Surf., A 323 (2008) 50–55.

[18] S. David, K. Sefiane, L. Tadrist, Experimental investigation of the effect of thermal properties of the substrate in the wetting and evaporation of sessile drops, Colloids Surf., A 298 (2007) 108–114.

[19] Intel, Intel Xenon Processor E5-1600/E5-2600/E5-4600 Product Families, vol. 1, 2017.

[20] Intel, Intel Core i7-900 Desktop Processor Extreme Edition Series and Intel Core i7-900 Desktop Processor Series, vol. 1, 2010.

[21] C. Yunus, J. Afshin, Heat and Mass Transfer: Fundamentals and Applications, 5th ed., Tata McGraw-Hill, New Delhi, India, 2011.

[22] S. Dash, S.V. Garimella, Droplet evaporation on heated hydrophobic and superhydrophobic surfaces, Phys. Rev. E 89 (2014) 042402.

[23] P. Kelly-Zion, C. Pursell, S. Vaidya, J. Batra, Evaporation of sessile drops under combined diffusion and natural convection, Colloids Surf., A 381 (2011) 31–36.