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ANALYSIS AND OPTIMIZATION OF ACTIVATED CARBON COATED HEAT SINKS

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Abstract: With the enhancements in nanotechnology, electronic devices shrank in size which led to a necessity to develop efficient thermal management strategies. These small electronic devices could be thermally managed through passive systems provided that effective materials are developed. Here, we use a layer of activated carbon on top of anodized aluminum heat sinks to utilize the sorption cycle of atmospheric water to create a desorption induced evaporative cooling effect. The material properties of the activated carbon lead to enhanced cooling by radiation and desorption, while the geometry of the heat sinks ensure surface area maximization. We develop a numerical simulation platform to determine the optimum geometry and the optimal activated carbon coating mass. Our results show that as the fin diameter and spacing shrink, and as the activated carbon mass increases within the considered range (0-100 mg), effective cooling of the chip could be achieved. We further employ our simulations to decouple the effects of desorption, radiation, and convection. Our analyses reveal that desorption only plays a vital role during the initial periods of operation, while cooling due to radiation and convection leads to an ≈20% increase in the overall steady-state heat transfer coefficient. This study goes beyond introducing a passive thermal management strategy for small electronic chips by providing a link between mass diffusion and thermal processes for effective transient operation of thermal devices.
Keywords: Thermal management, Activated carbon, Passive device, Heat sink.

AKTİF KARBON KAPLAMALI SOĞUTUCULARIN ANALİZ VE OPTİMİZASYONU

Özet: Nanoteknolojideki son gelişmeler, elektronik cihazların boyutlarının küçülmesine yol açtı ve bu durum randımanlı ısıl yönetim stratejilerinin geliştirilmesini bir zorunluluk haline getirdi. Küçülen bu cihazların ısıl yönetimlerinin geliştirilecek olan verimli pasif cihazlar vasıtasıyla etkili bir şekilde gerçekleştirilebileceği öngörülmektedir. Bu çalışmada, atmosferdeki su buharının sorpsiyon döngüsü kullanılarak yapay bir buharlaşmalı soğutma etkisi oluşturulması amacıyla anotlanmış alüminyum soğutucuların üzerine bir aktif karbon tabakası kaplanmıştır. Aktif karbonun malzeme özellikleri radyasyon ve desorpsiyon ile daha fazla soğutmaya olanak sağlarken, ısı emicilerinin geometrileri yüzey alanının en üst seviyeye çıkarılmasını sağlamaktadır. İdeal soğutucu geometrisini ve optimum aktif karbon kaplama kütlesini belirlemek için sayısal benzetim platformları geliştirilmiş ve kullanılmıştır. Analiz sonuçlarına göre kanatçık çapı ve aralığı küçüldükçe, ve aktif karbon kütlesi çalışılan aralıkta (0-100 mg) arttıkça, elektronik çipin etkili bir şekilde soğutulabildiği görülmektedir. Desorpsiyon, radyasyon ve konveksiyonun etkilerini ayrı ayrı çalışabilmek için belirli girdilerle benzetme algoritmaları tekrar kullanılmıştır. Analizlerimiz, desorpsiyonun sadece erken fazlarda önemli bir rol oynadığını, radyasyon ve konveksiyon temelli soğutmanınsa denge durumundaki toplam ısı transfer katsayısında ortalama %20'lik bir artışa yol açtığını ortaya koymaktadır. Bu çalışma küçük elektronik cihazların pasif yöntemlerle soğutulmalarına yönelik stratejiler geliştirmenin ötesinde, ısıl cihazların zamana bağlı etkili bir şekilde çalışmaları için kütle difüzyonu ve ısıl prosesler arasında bir bağlantı kurmaktadır.
Anahtar Kelimler: Isıl yönetim, Aktif karbon, Pasif cihazlar, Isı emici.

NOMENCLATURE

A	Area [m^2]
AC	Activated Carbon
C	Concentration [mol/mol]
c_p	Specific Heat Capacity [kJ/kg·K]
D	Fin Diameter [mm]
D_C	Intramolecular Diffusivity [m^2/s]
g	Gravitational Acceleration (m/s^2)
h	Heat Transfer Coefficient [W/m^2·K]
IoT	Internet of Things
k	Thermal Conductivity [W/m·K]
L	Length of the Fin [mm]
L_1	Length of the Chip [mm]
L_2	Width of the Chip [mm]
L_C	Characteristic Length [m]
m_w	Mass of Adsorbed Water [mg]
m_{AC}	Mass of AC Coating [mg]
MOF	Metal-Organic Framework
N	Number of Fins

Nu	Nusselt Number [$=h \cdot L/k$]
P	Perimeter [mm]
q_c	Heat Supply [W/m^2]
r	Radius [m]
R	Thermal Resistance[K/W]
R_s	Particle Radius [nm]
Ra_L	Rayleigh Number [$=\beta \cdot g \cdot \Delta T \cdot (L_C)^3/\nu \cdot \alpha$]
RK4	4th Order Runge-Kutta Algorithm
S	Fin Spacing [mm]
t	Time [s]
T	Temperature [K]
t_C	Thickness of the Chip [mm]
α	Thermal Diffusivity (m^2/s)
β	Thermal Expansion Coefficient (1/K)
ν	Kinematic Viscosity (m^2/s)
ΔT	Temperature Gradient [°C]
ε	Emissivity
η	Fin Efficiency
σ	Stefan-Boltzmann Constant [$W/ m^2 \cdot K^4$]

Subscripts

air	Air
des	Desorption
E	Inside the Silicon Chip
f	Fin
hot	Hot Side of the Silicon Chip
i	i'th Body
nat	Natural Convection
o	Overall State
rad	Radiation
s	Surface
t	Total
∞	Ambient

INTRODUCTION

With the recent advancements in nanotechnology, efficient small electronic devices to power Internet-of-Things (IoT) devices have proliferated (Yoon et al., 2015). While scaling down on the size brought about a plethora of advantages, it also led to certain engineering challenges to address to keep the output power at an acceptable range (Zhu et al., 2013). One of the bottlenecks of reducing the size of power electronics and IoT devices is the sheer thermal stresses arising from large thermal gradients, leading to material failures if not properly addressed (Yang et al., 2018). Therefore, thermal management of small devices has been a popular topic of research over the last few decades (Moore and Shi, 2014). Thermal management has been traditionally performed through heat sinks, where the exposed surface area is enhanced through elongated fins with optimized geometries to effectively decrease the temperature of power electronic devices (Hetsroni et al., 2002). While heat sinks enhanced the heat transfer with the surroundings significantly when a liquid flow was present, the enhancements were limited in the absence of a flow (Christen et al., 2016). Hence, other mechanisms of thermal management were introduced including radiative cooling (Zhou et al., 2016) and phase change heat transfer (Cho et al., 2016).

Radiative cooling refers to enhancing the emissivity of a body at the desired spectral range such that the emitted radiation from the surface is increased (Hossain and Gu, 2016). While this approach proves effective for systems that are not exposed to a running flow, design of selective emitters is a challenging task (Hahn, 2010). Thus, the operation of such systems is limited. Furthermore, exposing these devices to sunlight could result in the opposite effect (i.e. heating instead of cooling) since absorption and emission are equal at a spectral level (Hu et al., 2018). Therefore, performance enhancement stemming from radiative cooling is highly application specific.

Another technique to efficiently cool power electronics is to utilize the latent heat of phase change on hot spots of interest (Oh et al., 2017). High latent-to-specific heat ratio values of most liquids make phase change induced thermal management attractive for different applications (Günay et al., 2017). Hence, it has been extensively studied in the past (Attinger et al., 2014), especially through evaporative cooling (Günay et al., 2021), and boiling (Li et al., 2019). While boiling is effective due to significantly larger heat transfer coefficient stemming from bubble dynamics (Zhou et al., 2021), it is only meaningfully useful at high output power electronics due to the required high temperature spots to catalyze boiling (Birbarah et al., 2020). Therefore, evaporative cooling is much more desirable for small electronics where the temperatures are kept close to the standard room temperature or the human body temperature. Thankfully, evaporative cooling also results in significant enhancements in the heat transfer coefficient (Yang et al., 2019). In fact, studies attained as much as 91% enhancement through evaporative cooling due to efficient utilization of the latent heat of water evaporation (Kabeel et al., 2017). Therefore, evaporative cooling remains as a thermal management technique with a significant potential (Yang et al., 2019). On the other hand, while phase change heat transfer comes with many advantages, there are certain bottlenecks associated with it. A constant supply of fresh liquid needs to be integrated into the system, adding to the complexity, cost, and size (Birbarah et al., 2020). Furthermore, droplets have to be actively directed onto the hot spots, resulting in expenditure of energy to decrease the total conversion efficiency (Shahriari et al., 2017). Therefore, these bottlenecks have made it difficult for evaporative cooling inducing systems to be integrated into small electronics and IoT devices.

Recently, passive coatings that could utilize the sorption cycles of atmospheric water have been introduced (Rezk et al., 2012). These coatings constantly adsorb and desorb the humidity in the air to create sorption cycles due to their material properties (Kim et al., 2018). Silica gels (Ng et al., 2001), metal-organic frameworks (MOFs) (Kim et al., 2017), and zeolites (Henninger et al., 2010) have been primarily used for this purpose. While the main use of these materials and their corresponding sorption cycles has been to collect fresh water from the atmosphere (Fathieh et al., 2018), they were also shown to act as effective evaporative coolers since desorption creates a pseudo-evaporative cooling effect on the surfaces (Karamanis et al., 2012). Researchers from Shanghai Jiao Tong University in China used MIL-101 (a Chromium based MOF) to effectively thermally manage a 1W power generator, decreasing the maximum temperature as much as 8.6°C (Wang et al., 2020). Similarly, researchers from The University of Tokyo parametrically studied three different types of MOFs to display as much as 300% enhancement in thermoelectric power output for a device operating near room temperature (Günay et al., 2022). Though these results are promising, MOF powders are typically expensive and difficult to procure (Stock and Biswas, 2012). Therefore, a long way has to be covered before making these materials fully attractive for small scale operations.

Activated carbon (also termed activated charcoal) is another material with the ability to create water sorption cycles due to the material properties it possesses (Do and Do, 2000). It is cost effective compared to MOFs due to its vast availability and ease of procurement (González-García, 2018). Furthermore, activated carbon (AC) powders could be made to possess characteristic sizes in the microscale or nanoscale (Juárez-Galán et al., 2009). Furthermore, they could easily be applied onto surfaces through spraying (Jang et al., 2013). Since AC possesses a high radiative emissivity ($\varepsilon \approx 1$) (Subrenat and Le Cloirec, 2003), they could also be used as radiative coolers. Hence, AC coatings could be tailored as combined radiative and sorbent coolers.

In this study, we numerically investigate the use of AC coatings as efficient thermal management options. We consider aluminum pin fins coated with activated carbon powders to maximize the surface area, radiative cooling, and desorption from the surface. We determine the optimum fin diameter, spacing, and sorbent coating mass through numerical optimization considering the thermal management of a hot silicon chip. Our results show that low diameter and low spacing leads to the optimum geometry due to the maximization of the exposed surface area. Additionally, the results of our optimization reveal that the mass of the AC coating should be maximized within the studied range due to the enhancements in radiative cooling and the benefits of desorption cooling. We further utilize our numerical algorithms to determine the physical mechanism of enhancement. Our results reveal that while desorption plays a role in the early stages of operation, it has a negligible contribution to the performance in the steady- state. Rather, increased radiation and natural convection from the surface result in an ≈20% increase in the overall heat transfer coefficient for the AC coated heat sinks compared to the plain anodized aluminum ones. This study not only sheds light onto the use of AC coatings as an effective thermal management strategy but also provides design priorities for the next generation of sorbent based thermal systems.

SYSTEM MODEL

The system of interest consists of an aluminum heat sink with pin fins coated with a thin layer of AC (Figure 1). Aluminum is chosen because of its relatively high thermal conductivity for a fraction of the cost of other metals (Sommer, 1997). Furthermore, aluminum heat sinks could be anodized to increase their overall emissivity (Gustavsen and Berdahl, 2003). The heat sinks to be modeled in this manuscript are all anodized in order to obtain a fair comparison between the AC coated heat sinks and the plain ones. The heat sink serves as a thermally conductive mold with a high surface area, while the thin AC layer that takes the shape of the heat sink serves to create water sorption cycles to induce evaporative cooling, as well as to enhance the overall emissivity of the surface to increase cooling by radiation. The inputs for the numerical model related to AC were obtained from the literature and are summarized in Table 1 (Uddin et al., 2018, Verma et al., 2019).

AC was selected as the coating material due to its cost effectiveness and coatability. AC could be synthesized through many different techniques in vast amounts, leading to a low cost (Nor et al., 2013, González-García, 2018). In fact, commercial AC powders could be purchased from commercial vendors at around 0.132 $/g (7440-44-0, Sigma Aldrich), which places the cost of coating for this application to 0.013 $. Furthermore, bulk coatings could be easily applied following a procedure similar to the one given in previous studies (Günay et al., 2022). Therefore, considering the offered advantages of enhanced thermal performance and passive operatability at a low cost, AC coatings could potentially render the anodization process irrelevant for applications where the heat sinks are not subjected to heavy rain or flows.

A total silicon nanowire based chip size of 30x30 mm (L_1xL_2) was selected as a reference. The size of the heat sink was identical. The thicknesses of the base plate of the heat sink and the silicon chip were both 1 mm (t_C), while the fin length was selected as 3 mm (L). The spacing (S) and the fin diameter (D) were parametrically varied in the analyses to obtain the optimum fin geometry. Furthermore, the mass of the AC layer was altered along with the geometric parameters to determine the optimal coating thickness. All inputs were provided to the numerical code developed in MATLAB to obtain the temperature reduction and the heat transfer enhancement.

THEORETICAL MODELING

The theoretical model consisted of two main parts, namely; 1) mass diffusion model to obtain the desorption characteristics of water vapor on the AC layer, 2) a 1D transient heat transfer model to obtain the temperature gradients and the heat fluxes on the system. Assuming spherical particles undergoing homogeneous diffusion at a given temperature, the change in concentration is given by Fick's Law as (Stebe and Lin, 2001):

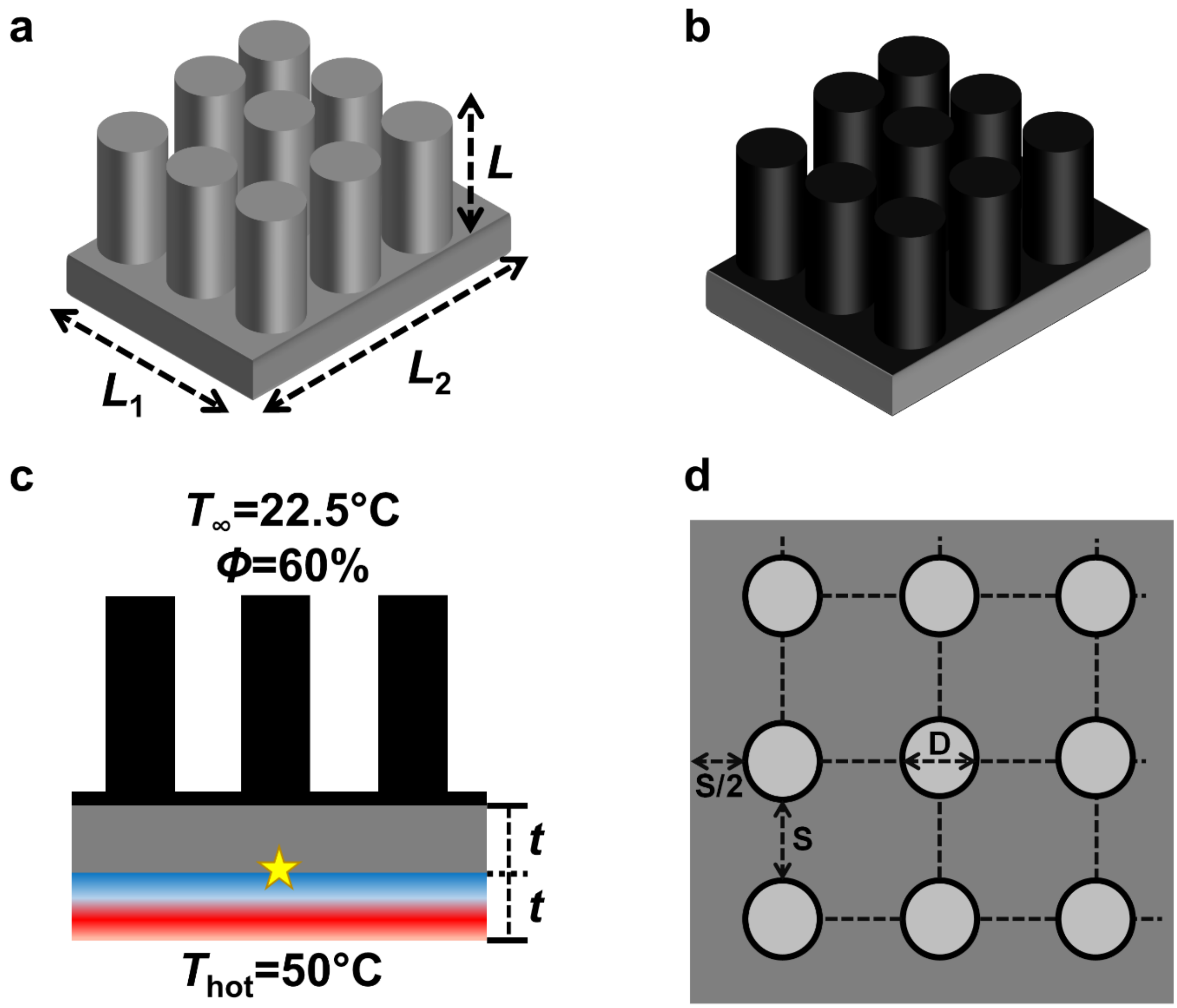

Figure 1. Schematics of the modeled system. a) The anodized aluminum heat sink with the corresponding dimensions, b) activated carbon coated anodized aluminum heat sink, c) side view of the modeled system including the electronic chip, the base of the anodized aluminum heat sink, and the activated carbon coating. The star represents the top side of the electronic chip which is the spot (the whole top surface) to be cooled. d) Top view of the modeled system with the corresponding geometric shape factors.

$$\frac{\delta C}{\delta t} = \frac{D_c}{r^2}\frac{\delta}{\delta r} r^2 \frac{\delta C}{\delta r}, \tag{1}$$

Assuming constant surface concentration, diffusivity, and intermolecular radius, the solution of Eq. (1) reduces to (Kim et al., 2018):

$$\frac{m_w}{m_{AC}} = \left[1 - \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n^2\pi^2 D_c}{R_s^2}t\right)\right], \tag{2}$$

where the left hand side of Eq. (2) refers to the adsorption capacity of AC (14% at 60% relative humidity on average) (Rodríguez-Mirasol et al., 2005). We determined R_s=9.5 nm from the literature (Yuan et al., 2016) and subsequently obtained D_c=1.4x10^{-21} m^2/s through fitting Eq.(2) to match the adsorption capacity of AC. After obtaining the mass diffusion dynamics, the next step was to use them as inputs of the heat transfer calculations. Thermal information could be obtained at any given time by a mathematical balance of the total unsteady heat, radiation, convection, mass diffusion induced heat fluxes, and the total heat supply into the system. Assuming 1-D transport and that the spatial variations do not lead to any temporal changes in the thermal behavior, we could obtain the resulting governing equation with the corresponding boundary conditions as:

$$\sum_i m_i c_{p,i}\frac{dT_i}{dt} = A_s[q_c - h_{nat}(T_s - T_\infty) - \varepsilon\sigma(T_s^4 - T_\infty^4)] - \dot{m}h_{des}, \tag{3}$$

$$T_s(t=0) = T_\infty, \tag{4}$$

$$q_c - h_{nat}(T_s(t=\infty) - T_\infty) - \varepsilon\sigma(T_s^4(t=\infty) - T_\infty^4) = 0 \tag{5}$$

The 1-D assumption allowed us to effectively carry each intermediary temperature to the surface through the heat supplied from the silicon chip given by:

$$q_c = \frac{T_{hot} - T_s(t)}{\sum_i R_i}, \tag{6}$$

The resistance term was obtained by treating the silicon chip, the base of the heat sink, and the AC layer as slabs

Table 1. Property inputs for the numerical algorithm.

	Silicon Chip	**AC**	**Anodized Aluminum**
c_p **(kJ/kg·K)**	720	850	900
k **(W/m·K)**	0.25	0.63	205
ρ **(kg/m^3)**	2330	400	2700
ε	-	0.99	0.8

($R_i=L_i/k_i \cdot A_i$, with their corresponding cross sectional areas), obtaining the resistance of the extended fins (AC coated or plain) through fin efficiency analogy, and considering a 200 μm thick air gap as a contact resistance between the heat sink and the silicon chip (Günay et al., 2022). Thermal parameters that are necessary for the simulation of each layer are given in Table 1. Total fin efficiency and the corresponding thermal resistance were obtained from (Bergman et al., 2011):

$$\eta_o = 1 - \frac{NA_f}{A_t}(1-\eta_f) = \frac{1}{R_o h A_t}, \qquad (7)$$

where the subscript o represents the overall state (array of fins and the base), f represents the fin, and t represents the total. The individual fin efficiency for a pin fin was obtained from (Bergman et al., 2011):

$$\eta_f = \frac{\tanh\left[\left(\frac{4h}{kD}\right)^{0.5} L_C\right]}{\left(\frac{4h}{kD}\right)^{0.5} L_C}, \qquad (8)$$

where L_C=L+(D/4) is the characteristic length. Natural convection term was obtained through Nusselt-Rayleigh analogy for a heat plane facing upward given by (Bergman et al., 2011):

$$h_{nat} = \frac{Nu L_C}{k_{air}} = \left(0.54 {Ra_L}^{0.25}\right)\frac{L_C}{k_{air}}, \qquad (9)$$

Where $L_C=A_S/P$ was the characteristic length of the heat exchanging surfaces (fins). Finally, the mass information obtained by Eq. (2) was not enough for the solution of Eq. (3). We numerically differentiated Eq.(2) at each instant of interest to obtain the rates of desorption and used it as an input for Eq. (3). The latent heat of desorption of water from the surface was determined to be 55 kJ/mol from the literature which was lower compared to the 135 kJ/mol for evaporation of water (Kim et al., 2016).

The solution scheme of Eq. (3) consisted of a 4th order Runge-Kutta algorithm (RK4) solving Eq.(3) bounded by Eq.s (4)-(5). The effects of the intermediary temperatures (i.e. everything other than T_s) was transformed into the heat supply from the silicon chip using the resistances and effective parameters, and the corresponding surface temperatures were iteratively obtained for each second. The RK4 algorithm was tested with reference cases and validated before the implementation for this study. The reference cases for validation included heat sink scenarios with analytical solutions (without the effects of desorption), comparison to previously performed experiments with heat sinks and flat plates with sorbent coatings (without the effects of desorption), and comparison to previously performed experiments with sorbent coatings undergoing regular thermal operation (Günay et al., 2022). After we ensured that the algorithm was in perfect agreement with the analytical solutions (i.e. ≈0% deviation) and in good agreement with the experiments (within ≈10% of the experimental measurements), we implemented our numerical platform to carry out the thermal simulations.

RESULTS AND DISCUSSION

The main goal of this study is to minimize the temperature of the top surface of the silicon chip (Depicted with a star on Figure 1c). Therefore, the temperature reduction inside the silicon chip (ΔT_E) should be maximized. In other words, the effective heat transfer coefficient based on the top surface of the silicon chip (h_E) needs to be maximized. For that purpose, an optimization algorithm was carried out on top of Eq. (3) to determine the optimum geometry of the heat sink and the optimal AC layer mass. The analyses were carried out for a fin diameter range (D) of 0.5-10 mm, fin spacing to fin diameter ratio (S/D) of 0.1-29 with the condition the combination returned integer values of total number of fins (N), and an AC coating mass range of 0-100 mg (0 mg represents plain heat sink without any coating). Here it should be noted that 100 mg was chosen as an average practical maximum value for the applied coatings. Application of more mass would result in a higher activated carbon thickness, reducing the effective thermal conductivity, or increasing the packing ratio to decrease the ability to desorb effectively. Optimization was performed for maximum average temperature reduction inside the silicon chip (ΔT_E) over a period of 60 min. The results are given in Figure 2a. The results reveal that the optimal case (ΔT_E=5.9 °C, enabled by average h_E≈67 W/m^2·K) happens when the fin spacing and the fin diameter are equal (specifically for a fin diameter of 0.5 mm, yielding 900 fins) and for an AC coating mass of 100 mg. This is attributed to the enhancements in the surface area owing to the use of fins, and the increased cooling enabled by desorption and radiation owing to the presence of the AC layer. It is further seen that low S/D typically yields better cooling performance due to the increased number of fins, effectively increasing the exposed surface area. Furthermore, increasing the AC coating mass results in better cooling from the surface owing to the enhanced emissivity and the utilization of the sorption cycle of water. Therefore, we could postulate that the reduction in the effective thermal conductivity because of the presence of the AC layer does not contribute negatively to the cooling performance. On the other hand, our numerical analyses show that the maximum heat transfer coefficient is achieved for a coating mass of 115 mg for the determined optimal geometry, yielding an average overall heat transfer coefficient of h_E≈68 W/m^2·K. Furthermore, a coating mass of 166.2 mg further reduces the heat transfer coefficient to the value without the AC coating (h_E≈56 W/m^2·K), and 180 mg coating leads to the case of a flat plate (h_E≈15 W/m^2·K) due to the lower effective thermal conductivity of AC, leading to less

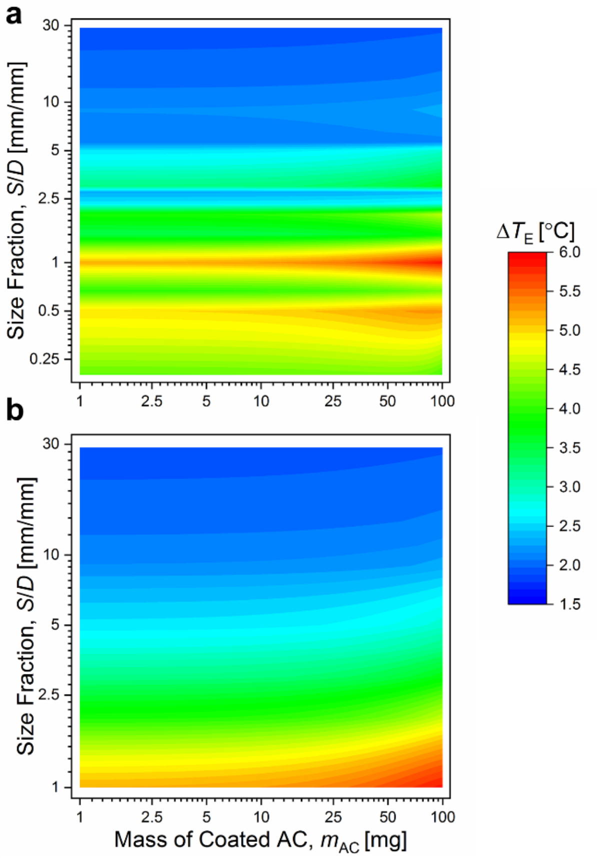

Figure 2. Results of the optimization analysis. The y-axis represents the geometry of the heat sink, the x-axis represents the activated carbon coating layer, and the colors represent the cooling performance (blue denoting minimum performance and red denoting maximum performance). a) The optimization results for all of the considered diameters, b) the optimization results for D=0.5 mm.

effective cooling from the surface. Hence, the practical limits should be carefully observed before applying the coatings on the heat sinks. Further investigation of Figure 2a reveals that the data does not follow a specific trend (especially for a *S*/*D* range of 1-5) due to thermal dynamics related to the changing diameter of the fin. Therefore, it is more useful to look at each studied diameter individually. For this purpose, we plot the optimization curves of the ideal diameter (D=0.5 mm) in Figure 2b. Results show that the cooling performance is reduced as the fin spacing increases, and the cooling performance is enhanced with a thicker AC coating due to the added desorption and radiation. Additionally, it is seen that the shortcomings of the fin geometry could be reversed through AC coatings (i.e. same temperature reduction could be obtained by depositing more AC). Therefore, we can conclude from our analyses that AC coated heat sinks hold great potential for commercial use as chip coolers.

After having obtained the optimal geometry and the AC mass, it was mandatory to get the physical reasoning behind this scenario. For that purpose, we determined the water desorption dynamics from the AC layer. The water uptake information of AC powders was obtained through the solution of Eq. (2) with the given parameters (R_s=14 nm and D_c=3x10^{-21} m^2/s) and is shown in Figure 3. We can clearly notice from the results that the low adsorption capacity of AC limits extra desorption from the surface. The rate of desorption is high at the initial contact owing to the rapid increase in the layer temperature; however, it becomes insignificant after 5-10 min. If the commercial AC powders could be treated to enhance their water uptake capacities through chemical treatments, the performance of these heat sinks could be drastically increased. Hence, further studies are needed to procure AC powders suitable for water harvesting.

Figure 4 shows the transient behavior of the temperature reduction inside the silicon chip (ΔT_E) and the heat transfer coefficient at the top side of the silicon chip (h_E) both for a plain heat sink with the optimal geometry (dotted lines) and the identical heat sink coated with 100 mg AC (solid lines).

Results reveal that while the plain heat sink itself is highly effective, reaching an average temperature gradient of ≈5 °C, the AC coating prevails in terms of performance due to the added radiation and desorption despite the lower effective thermal conductivity it possesses. Additionally, the overall heat transfer coefficient of the AC coated heat sink at the steady-state is 20% higher than that of the plain heat sink, proving the effective cooling capacity of the proposed devices. Considering all these benefits in terms of cooling performance, AC coated heat sinks can be deployed as cheap and effective thermal management solutions to replace the anodized aluminum heat sinks.

A breakdown of the mechanisms contributing to the enhancement in the cooling performance is given in Figure 5. A close investigation reveals that desorption plays a minor role in terms of enhancing the cooling performance, only contributing significantly within the first few minutes. This could be attributed to the low adsorption capacity of AC and the high temperature of the silicon chip. This contribution could be enhanced by increasing the coating mass, chemically treating the AC

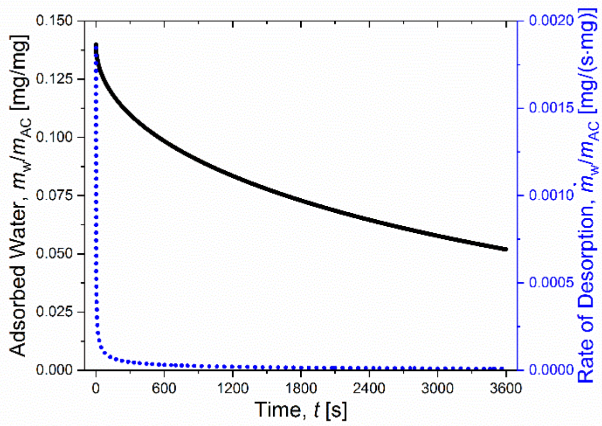

Figure 3. Dynamics of desorption in the activated carbon layer. The black curve (left-side) represents the transient desorption of the adsorbed water from the layer (normalized). The blue dots (right side) represent the corresponding dimensionless rate of desorption.

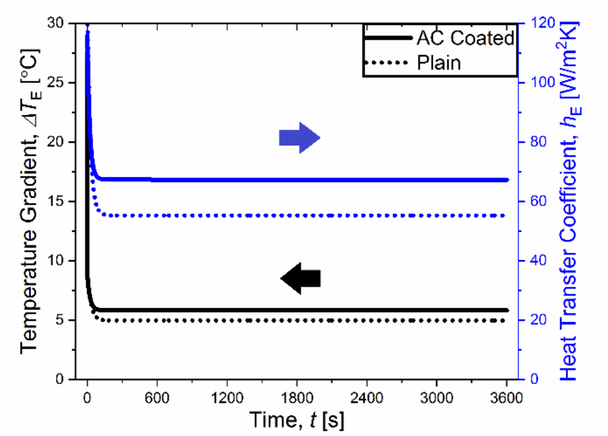

Figure 4. The transient cooling performance of the studied heat sinks. Black color (left-side) represents the temperature gradient within the electronic chip. Blue color (right-side) represents the corresponding overall heat transfer coefficient. Solid lines represent the activated carbon coated heat sinks. Dots represent the plain anodized aluminum heat sinks.

to increase its adsorption capacity, and controlling the pore size to regulate the desorption rate of water from the surface. These improvements were beyond the scope of this study. Additionally, we see that the contributions of both natural convection and radiation significantly increased to enhance the overall steady-state heat transfer coefficient by ≈20%. Additionally, our studies also revealed that anodized aluminum flat plates only displayed a steady-state heat transfer coefficient of ≈15 $W/m^2 \cdot K$, revealing the importance of surface area improvement through the use of extended surfaces (fins). Thus, we can safely postulate that a combination of increased emissivity, increased surface area, and the utilization of sorption cycles of atmospheric water can lead to highly effective passive thermal management of electronics. Furthermore, AC coated heat sinks are more effective than anodized aluminum heat sinks as revealed throughout this manuscript and can be potentially utilized as readily available electronic chip coolers.

CONCLUSIONS

Passive activated carbon coatings were employed as a passive thermal management solution for low output power electronics. We considered anodized aluminum heat sinks with pin fins and coated them with layers of activated carbon to utilize the sorption cycle of atmospheric water to induce a pseudo-evaporative cooling effect on the surface, and to increase cooling by radiation. In order to study the cooling performance of our envisioned heat sinks, we developed a 1D transient optimization model combining mass diffusion due to desorption and thermal contributions due to radiation, heat supply, conduction, and natural convection. Our numerical optimization revealed that a low diameter and low spacing yielded optimal cooling scenarios due to the enhancement of the total number of fins which leads to an increase in the exposed surface area available for heat exchange with the surroundings. Furthermore, our optimization results revealed that the mass of AC coating layer needs to be maximized within the given limits (100

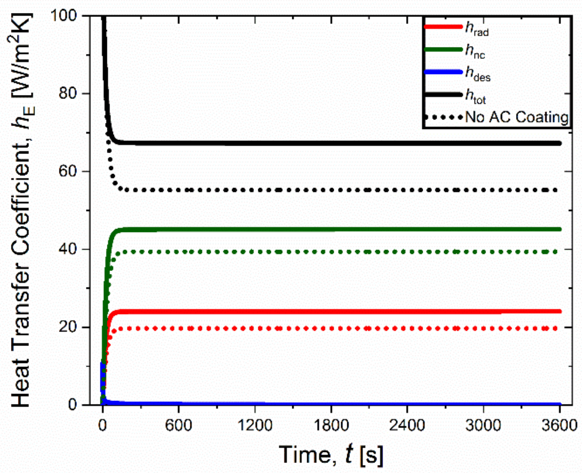

Figure 5. Decoupled effects of radiation, desorption, and natural convection. Solid lines represent the activated carbon coated heat sinks. Dots represent the plain heat sinks. Red denotes radiation, green denotes natural convection, blue denotes desorption, and black denotes the overall heat transfer coefficient.

mg for this study) to effectively employ evaporative cooling in the initial periods of thermal management, and to increase radiative cooling from the surface owing to increased emission. Our optimal heat sink design of 0.5 mm fin spacing, 0.5 mm fin diameter, and 100 mg activated carbon coating displayed a remarkable overall steady-state heat transfer coefficient of 67 $W/m^2 \cdot K$ in the void of fluid motion (i.e. still air) on the hot side of the electronic chip with room for further improvements through material development. The presence of the AC layer produced an ≈20% increase in the cooling performance when compared to the plain anodized case, showing that AC layers could be utilized on aluminum heat sinks instead of the anodized natural oxide layer. We further uncoupled the effects of desorption, natural convection, and radiation and concluded that the enhancement mainly stemmed from radiation and convection with desorption playing a vital role only in the early phases of contact due to the low adsorption capacity of activated carbon and relatively high thermal gradients within the system. Future studies to enhance the adsorption capacity of activated carbon powders would be useful to boost the cooling performance of these layers to the maximum. This study sheds light on the use of sorbents as thermal management coatings and provides design priorities of the new generation of sorbents that could be deployed as passive evaporative coolers.

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