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Wettability-confined liquid-film convective cooling: Parameter study

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ABSTRACT

We study experimentally the cooling of a mm-thick, heat-spreading metal plate of O(10 cm^2) area, which is heated locally by an embedded heat source with area O(1 cm^2). A liquid jet impinges orthogonally on the plate several hydraulic diameters away from the localized heat source, and gets diverted on a surface track passing over the heated region, thus cooling the plate. Capillary-driven, directional transport of the cooling liquid (water) is achieved by rendering the metallic substrate hydrophobic and laying a wettable, diverging track on it, connecting the jet impact point at its narrow end with the heated region, which is either at the wider end of the track or around the half-way point. Cooling performance is evaluated in terms of sensible heat transfer at various flow rates for different track wedge angles and relative position of the heat source, a situation that emulates cooling of an integrated circuit (chip). The effect of thermocapillary stresses, which oppose the flow under certain conditions, is analyzed; effective strategies to overcome such effects are also devised and implemented. Finally, a thermocapillarity-resilient, multi-track design that exhibits superior performance (as compared to single-track designs) is rationalized and demonstrated. We observe that maintaining the track width below the capillary length of the working fluid is vital for improved cooling performance. Cooling can be improved by using multiple, narrow tracks fed by individual impinging jets or a track design that splits the jet into multiple streams laid over the heated domain. Heat removal rates of the order of 100 W/cm^2 are attained without phase change at coolant flow rates as low as ~1 mL/s and chip superheats of 65 °C. The approach opens up new opportunities for heat removing devices that rely on advective cooling facilitated by wettability-patterned metal substrates.

1. Introduction

Proper thermal management is crucial for a large number of engineering applications, which require smooth operation and increased lifetime of the participating components. A multitude of heat carriers has been used by researchers, such as air [1], water [2], dielectric liquids [3], and even more exotic media, like nanofluids [4] or doped semiconductor nanowires [5]. However, only a few methods have actually reached commercialization depending on the application and the associated cost or complexity of the approach. Different heat transfer techniques, including free, forced or mixed convection, sensible or phase-change heat transfer have been attempted in this pursuit. Phase-change heat transfer offers the advantage of large latent heat of evaporation, but is more difficult to implement because of the associated large changes in specific volume of the working fluid. Direct liquid cooling techniques deploy heat transfer through contact between a dielectric liquid and the heat transfer surface, eliminating the need of any thermal interface materials, and therefore, hold great promise [6]. Striking a balance between cooling performance, and design and operational simplicities of a technique is key to produce a highly competitive and effective approach.

Thermal management in small devices requires meticulous balance between the deployed cooling resource and the cooling performance. Researchers have devised numerous cooling techniques, such as by direct impingement of jet [7] and spray [8,9], flows through microchannels [10] and porous media [11,12], and thin-film evaporation [13,14]. Jet impingement cooling deploys a single, high-velocity jet exiting a nozzle, or an array of jets that impinge directly on the heated area, allowing for high heat transfer coefficients (HTC) around the impingement spot. However, as the jet (or the array of jets) spreads radially out, the local HTC significantly decreases away from the impingement spots. More importantly, the conventional jet-impingement cooling also lacks directionality – the liquid spreads in all directions and selective

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Nomenclature

g	acceleration due to gravity
h	heat transfer coefficient
k	thermal conductivity of fluid
L	length of diverging track
Nu	Nusselt number
n	number of parallel diverging tracks
Pr	Prandtl number
Q	jet volume flow rate
r	Single-track to multi-track width ratio
Re	Reynolds number
T	temperature
TC	thermocouple
u	velocity
We	Weber number

Greek letters

α	wedge angle
γ	surface tension
δ	local width of diverging track
ν	kinematic viscosity of water
ξ	water film thickness
ρ	density of water
σ	standard deviation
τ	Marangoni stress

Sub/Superscripts

FoC	forced convection
FrC	free convection
in	leaving the nozzle
Rad	radiation
split	splitter design with multiple tracks

preferential cooling of specific domains may not be possible. Spray cooling is highly efficient and relies on the spraying of small droplets impacting directly on the hot area; the high latent heat of vaporization of these droplets provides effective cooling as the droplets change phase. The technique requires precise coolant flow management, so that operation lies between the Leidenfrost (floating) regime and the flooding state of the substrate [15]. Microchannel cooling employs miniature flow channels, where the heat transfer coefficient is increased due to the reduced characteristic dimension (rendering greater surface-to-volume ratio) of these channels. However, heat transfer enhancement in these devices comes at the expense of increased pumping costs. This can be a potential concern, especially when it comes to electronics cooling, where the energy budget has to be optimized between computational and cooling requirements [16]. Utilization of porous media for cooling purposes follows the principle of increasing the heat transfer area between the solid and the cooling fluid by using metal foams or sintered particle structures [17]. This again suffers from high pressure-losses with the added disadvantage of manufacturing complexity for such materials. Finally, thin-film evaporation requires intricate structures on the substrate in order for the thin film to be maintained [18], which increases manufacturing costs and decreases durability. On the other hand, wettability patterning and the wide range of associated techniques that have been developed in this domain [19] offer a new opportunity for creating facile wettability-based fluid management methods well-suited for domain-specific surface cooling. Directing an impinging jet on the hot surface in a controlled fashion to achieve large heat transfer rate with minimum coolant deployment would require that the capillary force have to overcome the inertia force in the wall-jet that ensues upon jet impact. We achieve this through an intelligent design of wettability patterning; we show that wettability engineering is a simple, yet effective method of confining the cooling fluid where heat removal is most needed.

The present study advances the novel cooling approach proposed in our previous work [20], where jet impingement and wettability patterning were combined to selectively cool physically-inaccessible areas on a heated surface, where direct fluid impact could not be rendered. A wettable track of diverging width is laid on a functionalized superhydrophobic aluminum substrate; a vertically rising laminar water jet strikes orthogonally the narrow end of the track on the substrate (facing down) and gets fully diverted to the wider end, cooling a locally-heated area more than 27 hydraulic diameters away from the jet impingement location. Spreading of the water jet on the substrate in the transverse direction is confined by the wettability contrast, and aided in the longitudinal direction by the Laplace pressure difference owing to the diverging geometry of the tracks [21]. The system performance is studied in terms of sensible heat transfer from a substrate-embedded (on back side), localized source of heat ($\sim$0.9 cm^2) capable of producing heat fluxes of the order of 100 W/cm^2. Multiple track designs, flow rates and different relative positions of the heat source on the track are examined to optimize the device performance and explore its limitations. The flow rate regimes investigated are designated as *low* (69–71 mL/min), *medium* (86–88 mL/min) and *high* (115–117 mL/min); the *low* regime corresponds to the flow rate below which the vertically rising jet fails to touch the plate, while the *high* regime represents the flow rate beyond which the jet starts splashing on the plate. This approach delivers significant versatility to fully control the direction of flow and location of cooling on a heated substrate just by laying down the wettable tracks on the heat spreader, while diminishing pumping expenses related to microchannel or porous media cooling [22]. The technique also offers the opportunity to use an offset jet impingement arrangement, which is beneficial when the device complexity does not allow direct access of the impinging jet to the heated area. Sometimes offset impingement may be desired from the mechanical stand-point as well; one can coat the impingement point with an additional layer of abrasive material to prevent substrate erosion [23,24]; direct jet impingement at the heated area would warrant such coating to be provided locally, thus adding to the thermal resistance and lowering the heat transfer. Offset jet impingement allows separating the impingement location from the heated area, thereby circumventing this limitation.

2. Materials and methods

Two different wettability-patterning methods were used in the present work, both using the same type of aluminum substrate (6061 alloy, mirror-finish, McMaster-Carr) as a starting material. The first method followed the approach used in our previous work [20], where the aluminum plate was first acid-etched, passivated in boiling de-ionized (DI) water, functionalized with a fluoroalkyl silane, and finally, patterned by laser etching. The second method started with acid-etching the aluminum plates in a 4 M HCl solution and passivation in boiling DI water. Subsequently, the substrate was functionalized by spin-coating Teflon AF (Chemours AF 2400, 1% solution) at 2000 rpm for 20 s and then