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Supersonically spray-coated copper meshes as textured surfaces for pool boiling

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ABSTRACT

Pool boiling is a process through which heat is removed upon the vaporization of a coolant fluid surrounding a heated surface and is often applied for cooling high-performance computing systems and nuclear reactors. Increasing the surface-to-volume ratio in confined spaces enhances this cooling method. Here, we introduce textured copper pillars with various geometric arrangements and study their effects on the pool-boiling performance. Frustum pyramids were formed by supersonic spraying copper microparticles through a wire mesh to form pillars of various sizes. We identified an optimal pyramid-base size of 0.91 mm on each side corresponding to the maximum heat transfer coefficient, critical heat flux, boiling heat transfer, and cross-flow coolant velocity over the pyramids. Maximum bubble nucleation was also achieved using this specific geometric arrangement. Such a geometric design can be installed in heat pipe cooling systems to cool electronic devices and nuclear reactors.

1. Introduction

Server computing is an evolving technology that facilitates mobile internet devices and provides entertainment, information, and location-based services in real time. Most server-computing infrastructures offer services delivered through server clusters housed in data centers, which deploy computing hardware comprising high-density chips and high-throughput communication technologies that run software products specifically designed to deliver cloud services. The underlying market trend for data centers is to miniaturize servers, while increasing unit functionality. The resulting increase in heat flux poses enormous challenges for traditional thermal management methods using forced-air convection through finned heat sinks [1–4], which has become problematic, because the power consumption of computer room air conditioning now accounts for approximately 30% of a data center energy consumption [5–7].

Other technologies such as loop heat pipes, water cooling and immersion cooling, are receiving attention [4,8–14]. Loop heat pipes enhance air cooling, but have drawbacks associated with complicated fabrication and integration leading to high costs [15–17]. As opposed to air cooling, water cooling is less influenced by the ambient temperature inside the servers and thus cooling-energy requirements can be reduced. However, disadvantages include potential leakage, corrosion, significant weight, and the power required to pump water [18]. As an alternative, immersion cooling is highly efficient because it takes advantage of the direct contact between a heated surface and the coolant, as well as the large enthalpy of the corresponding phase change. For example, as depicted in Fig. 1, immersion cooling is not limited to one component, but can simultaneously cool entire systems, including CPUs/GPUs, RAM, power-supply units, and other components. Because this is a relatively complicated and expensive solution, immersion cooling has been a niche technology, used for high-power electronics applications such as military radar systems and high-speed trains [19]. Nevertheless, because thin server-rack units are only 4.3 -cm- thick with heat loads of 210–300 W [20], the immersion cooling is well-suited to data-center applications.

Heat transfer for immersion cooling leverages pool boiling, which can be optimized by increasing the critical heat flux (CHF) and the heat transfer coefficient (HTC). Nano-scale geometries employing surface texturing have been shown to enhance CHFs and HTCs in pool-boiling

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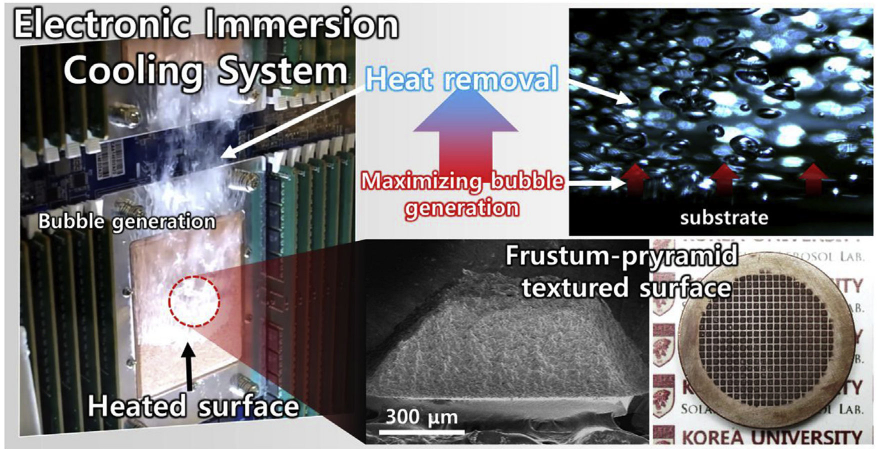

Fig. 1. Immersion cooling system.

applications [21–23]. In previous studies from this group, several nano-texturing methods have been demonstrated to enhance the CHF and HTC by separating liquid and vapor paths, ensuring sufficient liquid flow to cool a surface [24–27]. However, there remain challenges before nano-texturing can become a commercially viable method for the immersion cooling of electronics. To investigate the best approach for immersion cooling, this paper suggests a new nano-texturing technique using a metal-mesh mask and supersonic cold spray, which can be rapidly and scalably implemented. Texturing conditions and configurations are studied to identify nano-texturing structures that facilitate the effective release of bubbles from nucleation sites while providing a sufficient liquid supply to support rapid vaporization rates at high heat loads.

2. Experimental setup

2.1. Materials

Frustum pyramid-shaped pillars were constructed from 1-µm copper powder particles (LeesChem Co., Korea) [28]. The coolant was HFE-7100 (NovecTM Engineering Fluid, 3 M), which does not deplete the ozone and is many used in industrial applications including vapor degreasing and the cleaning of co-solvent parts because of its chemical and thermal stability, high vaporization heat, and low toxicity. The thermo-physical properties of the coolant are listed in Table 1 [29].

2.2. Micro-patterned frustum-pyramidal structure coating process

Supersonic cold spraying was used to uniformly pattern copper substrates with frustum-pyramidal pillars. The supersonic cold spray set up and mechanisms for forming the frustum pyramids are described in detail elsewhere [28].

Fig. 2a illustrates the coating process. The metal mesh consisted of wires (d = 0.4 mm) forming a 50 × 50 mm^2 mesh mask. Supersonic spraying was implemented using a compressor pressure of 6 bar at 320 °C. The distance between the nozzle and substrate was 55 mm. Cu particles were supplied through a powder feeder to coat the substrate, at a volumetric flowrate of 25 m^3/min. The nozzle was fixed, while the substrate was maneuvered at a speed of 35 mm/s. When the Cu particles collided with the substrate, their kinetic energy was converted into thermal, bonding, and adhesion energies [30]. The Cu particles adhered to the substrate effectively, and underlying particle layers and the frustum pyramid pillars exhibited no detachment from the substrate after several pool-boiling tests.

Table 1
Thermo-physical properties of HFE-7100.

Physical properties	HFE-7100 (0.1 MPa)
Boiling point (°C)	61
ρ_l (kg·m^{-3})	1370.2
ρ_g (kg·m^{-3})	987
μ_l (kg·m^{-1} s^{-1})	3.70 × 10^{-4}
σ_{lg} (N·m^{-1})	1.019 × 10^{-2}
c_p (J·kg^{-1} K^{-1})	1255
h_{fg} (J·kg^{-1})	111.6

2.3. Pool-boiling setup

The experimental setup for pool boiling, illustrated in Fig. 3, comprised the test chamber, a Teflon case, an aluminum rod, four heaters, three thermocouples, a Cu substrate with a length (L_{Cu}) of 10 mm and diameter (D_{Cu}) of 30 mm, three preheaters, and a coolant thermocouple. The condensation unit was composed of a chiller and a spiral glass tube.

A power supply (Slidac, 1 kV A, Dae Kwang Electric Co.) transferred heat to the aluminum rod, which has a length (L_{Al}) of 100 mm and diameter (D_{Al}) of 50 mm, with k_{Al} = 210 W m^{-1} K^{-1}, whose temperature was measured using three thermocouples (Omega Inc.) with accuracies of ± 0.3 °C. These thermocouples were monitored using a data recorder (Memory HiLogger, LR 8400, HIOKI) at three different vertical locations, spaced 8 mm apart, as shown in Fig. 3. The aluminum rod was enclosed in a Teflon case (k = 0.25 W m^{-1} K^{-1}) to minimize heat loss. Thermal grease (Dow Corning, TC-5026, k_g = 2.89 W m^{-1} K^{-1}) was used to fix the sample and reduce the contact thermal resistance between the sample and the aluminum rod.

The coolant was preheated to 60 °C using three 100-W preheaters. The condensation unit circulated cooling water at 5 °C through a spiral tube carrying water from the chiller (AP15R-30-V11B, VWR Ad). The bottom heaters of the aluminum rod were supplied with a power of 150 W to heat the entire rod and Cu substrate. When the coolant temperature did not change by more than ± 0.1 °C, pool boiling tests were initiated by increasing the thermal output by 15 W every 10 min.

2.4. Characterization

Cross sections of the Cu frustum-pyramid pillars were measured using a field-emission scanning electron microscope (FE-SEM, S-5000, Hitachi) at 15 kV. Snapshots from a CCD camera (Phantom 9.1, Vision Research Inc.) were used to measure capillary phenomena upon the sample being dipped into the coolant and bubble formation being observed. Capillary rises and contact angles in the snapshots were analyzed using a measurement solution (I'MEASER 3.0, ING. PLUS).