PRELIMINARY STUDY ON CAPILLARY-DRIVEN COOLING USING MICRO-METAL 3D-PRINTED POROUS MICRO-CHANNELS

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1. Introduction

Critical Heat Flux (CHF) limits the maximum allowable heat generation rate before vapor film formation causes a sudden excursion in surface temperature [1]. Surface modification techniques, such as micro/nano-texturing and porous coatings, enhance liquid replenishment and delay film boiling via capillary-driven flow [2]. However, conventional surface modification methods often present limitations in structural consistency, durability under high-stress environments, and geometric reproducibility [2].

Micro-additive manufacturing (3D printing) offers precise control over microscale features, channel tortuosity, and volumetric porosity. Although practical applications target critical heat flux (CHF) enhancement by preventing vapor blanket formation on heated surfaces, understanding fundamental capillary-driven liquid supply is essential prior to full-scale pool or flow boiling investigations. This study presents a fundamental proof-of-concept investigation into the fabrication of porous copper micro-channels on copper substrates using the micro 3D printing, evaluating the underlying capillary-driven liquid transport and its passive cooling potential to lay the groundwork for future boiling heat transfer and CHF enhancement.

2. Test section and preliminary test

2.1 Wicking Test

Test specimens were fabricated using paste-based metal extrusion. As shown in Fig. 1, micro-porous channel geometries were designed with varying channel widths (0.13 mm – 1.53 mm) to fundamentally investigate the trade-off between capillary driving pressure and viscous flow resistance, rather than targeting a single specific application device. The porous channel walls were fabricated from sintered Cu powder on a solid Cu substrate plate, providing dual capillary paths via both intra-wall micropores and inter-wall open channels.

Fig. 1. Micro-porous channels

The test specimen was positioned vertically, and water droplets were supplied to the bottom of the channels. As shown in Fig. 2, each channel exhibited a distinct wicking height depending on its geometry.

Fig. 2. Wicking test with water droplets (vertical channel)

2.2 Passive Cooling Test

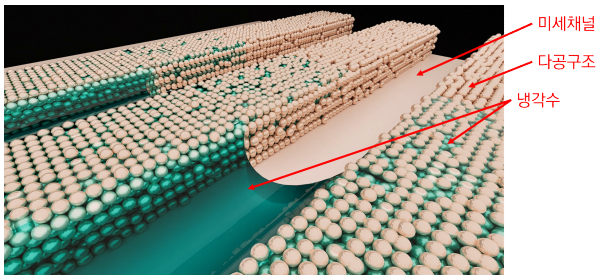

Fig. 3. Schematic diagram of capillary-driven water transport within the micro-porous channels.

Fig. 3 illustrates the working principle of water transport across the micro-porous channels. When one

end of the micro-porous structure contacts a liquid reservoir, water is drawn toward the dry region via capillary action. When applied to high-heat-flux components (e.g., electronic chips, localized heaters), the transported water evaporates upon absorbing heat. This evaporation creates localized dryout zones that induce further capillary suction, continually replenishing the heated area with liquid and sustaining passive evaporative cooling.

The passive cooling test was conducted using the fabricated test section shown in Fig. 4. The test assembly was mounted on a 5 cm x 5 cm Cu plate. A 20 mm x 35 mm ceramic heater was attached to one side of the Cu plate, and a thermocouple was embedded between the plate and the heater surface to monitor wall temperature. On the opposing side, porous Cu channels with a wall thickness of 0.4 mm, channel width of 0.4 mm, and height of 1.3 mm were fabricated. A designated bare margin was left along the plate edge for clamping. Fig. 5 shows the fully assembled test section.

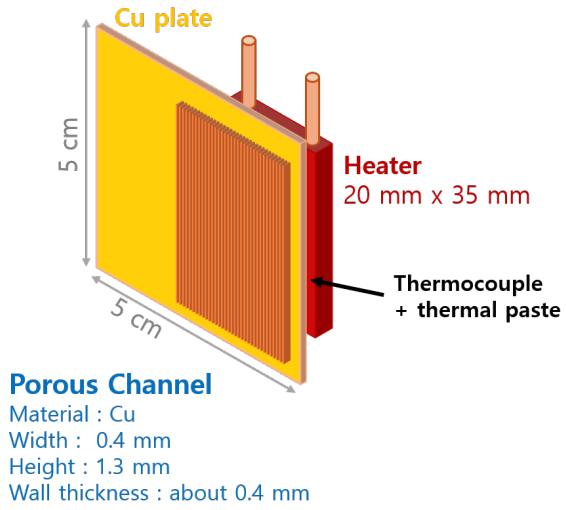

Fig. 4. Schematic diagram of test section for passive cooling

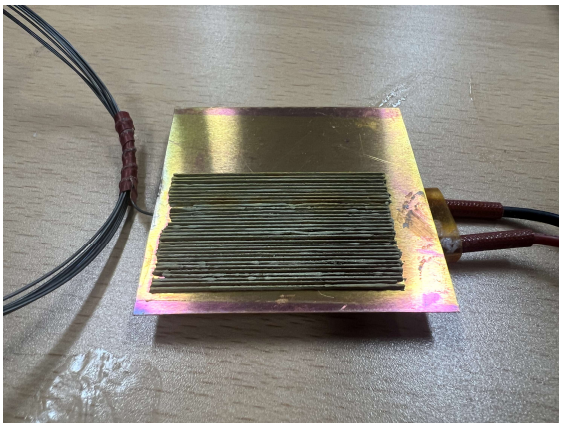

Fig. 5. Picture of test section for passive cooling

Two experimental cases were conducted to evaluate passive cooling performance:

1) Reference Test (Air Cooling): The test section was heated in ambient air. The heater surface temperature was recorded once steady-state conditions were reached at each electrical power input (represented by the red line in Fig. 6).

2) Passive Cooling Test (Wetted Channels): The bottom edge of the test section was submerged in a water reservoir, repeating the same stepwise heating procedure (represented by the blue line in Fig. 6).

The results demonstrate that the capillary-fed micro-porous surface significantly lowers the operating surface temperature compared to natural convection (e.g., maintaining ~140 °C at 45 W, whereas the dry surface reached 200 °C at only ~16 W), confirming its viability for passive thermal management. Physically, this substantial temperature reduction is achieved via continuous capillary-driven thin-film evaporation along the porous channel walls. Because the onset of CHF in boiling systems is triggered when localized vapor patches starve the heated surface of liquid, the robust passive liquid replenishment observed here provides a clear physical mechanism to suppress early dryout. While direct boiling curves and two-phase heat transfer coefficients remain to be characterized, the demonstrated self-driven liquid supply substantiates the potential of this structure to delay boiling crisis and elevate CHF limits in high-power applications.

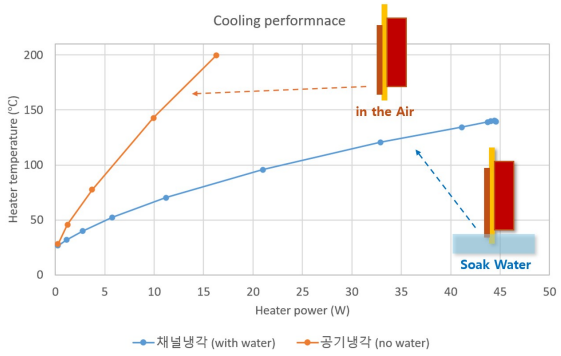

Fig. 6. Results of passive cooling test

3. Conclusions

In this study, porous copper micro-channels were fabricated via paste-based metal extrusion 3D printing, and their capillary transport and passive cooling performance were experimentally evaluated. Key findings include:

Capillary Wicking: Micro-porous channel geometries enabled spontaneous liquid uptake without external pumping, with wicking performance depending directly on channel dimensions.

Passive Thermal Management: Continuous capillary-driven replenishment sustained evaporative cooling, significantly reducing steady-state surface temperatures

compared to bare air cooling.

In the future, this technique can be applied to Critical Heat Flux (CHF) enhancement and various advanced heat transfer applications.

REFERENCES

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