High-Performance Two-Phase Cooling under Different Cold Plate Orientations

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***Abstract*—Two-phase cooling shows promise for data center applications due to the inherent high heat transfer coefficients, heat capacities, and isothermality associated with two-phase cooling. The dielectric nature of the available two-phase coolants is increasingly viewed as a benefit, as AI hardware continues to increase in cost, increasing the cost associated with water leaks. Skived copper cold plates are commonly implemented in data center liquid cooling due to their low cost and ability to achieve fin and channel sizes on the order of 100s of microns. The increasing chip level heat fluxes and rack level powers necessitate the rethinking of thermal packaging of chips and servers within racks. Thermal engineers are now considering the use of direct-to-chip liquid cooling solutions where the cold plates may be used in orientations that are atypical. This may include vertically orientated blades, two-sided CPU cooling, or servers oriented upside down (opposite to standard horizontal server orientation). Since two-phase cold plates inherently have vapor and liquid, each with different respective densities, the separation of the two phases is of concern in these alternative orientations. In this paper, we present results for two-phase cold plates in these other orientations, without any modification to the original cold plate design. The performance in these orientations was shown to vary both positively and negatively compared with standard horizontal operation, depending on orientation and applied power levels. Ultimately, the two-phase cold plate performance was proven to be sufficient in all orientations without any modification to the original cold plate.**

Keywords—liquid cooling, direct-to-chip two-phase cooling, high power processors, data center cooling, thermal management

I. Introduction

The thermal design power of CPU and GPU chips used in data centers are increasing rapidly with the artificial intelligence fueled demand for higher computational power [1]. Direct-to-chip two-phase cooling solutions using eco-friendly fluids have demonstrated the ability to meet these increasingly stringent thermal requirements for CPUs and GPUs [2-4]. The superior performance for two-phase systems at the rack level has also been demonstrated [5,6]. Recently, two-phase cold plates have been shown to outperform single-phase water even when the cold plates are not optimized for two-phase heat transfer [1,7].

Thermal engineers are interested in exploring cooling strategies that will require cold plate orientations that are not typical of standard cold plates. Fig. 1 shows a picture of a typical horizontal server (right) and a less common blade type server (left) [8,9]. The vapor and liquid present in two-phase cold plates have densities that are generally 2-3 orders of magnitude different at most operating conditions [10]. Therefore, when operating at different orientations, the phases will separate differently, causing different flow regimes to occur. To better understand the effects of these orientations, a typical flow boiling cold plate has been tested at several orientations to better understand these orientation effects empirically.

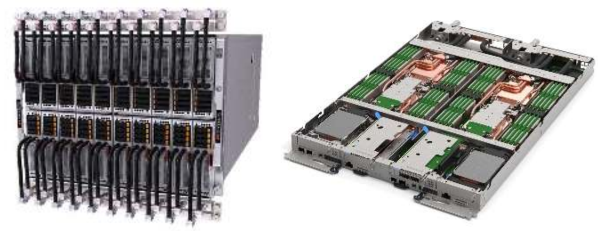

Fig. 1 (Left) Supermicro SuperBlade [8] with servers and cold plates in vertical orientation. (Right) Lenovo ThinkSystem SD650 V3 Neptune DWC Server [9] with horizontal upward cold plates.

II. Experimental

A thermal test vehicle (TTV) is designed and fabricated from a copper block, with a heated surface area of 26×35 mm^2. Cartridge heaters are inserted into the copper block to provide heating power. A K-type thermocouple probe is positioned beneath the center of the heated case surface. Given the heating power and copper thermal conductivity, the case temperature is obtained from the probe-measured temperature by assuming uniform 1D heat conduction towards the heated surface. A cold plate designed for a high-power GPU chip is attached onto the TTV with a phase-change based thermal interface material (TIM) sandwiched in between. Tests are conducted in a fluid circulation loop with R1233zd(E) as the working fluid. The inlet refrigerant flow rate is set at ~500 mL/min, and the heating power is varied from 0 to 2000 W. The fluid temperature at the outlet of the cold plate is measured. The case-to-fluid thermal resistance is calculated from the case temperature, the outlet fluid temperature, and the heating power [11]. Details of the experimental system and measurement techniques can be found in Refs. [3,12].

In this work, three different orientations were tested for each working condition, with the heated surface positioned as horizontal upward, horizontal downward, and vertical, as schematically shown in Fig. 2. The same cold plate/TTV assembly was tested without breaking thermal contact in between tests to avoid uncertainties caused by the TIM.

III. Test Results and Discussion

Fig. 2 presents the thermal resistance curves with varying heating power for the three orientation conditions. All curves show a similar trend, initially decreasing and then increasing with power. The initial decrease of thermal resistance with increasing power at low power range can be attributed to the reduced contribution from single-phase sensible cooling, which exists due to inlet subcooling and is less efficient than two-phase boiling. The lowest thermal resistance corresponds to the highest heat transfer coefficient under fully developed

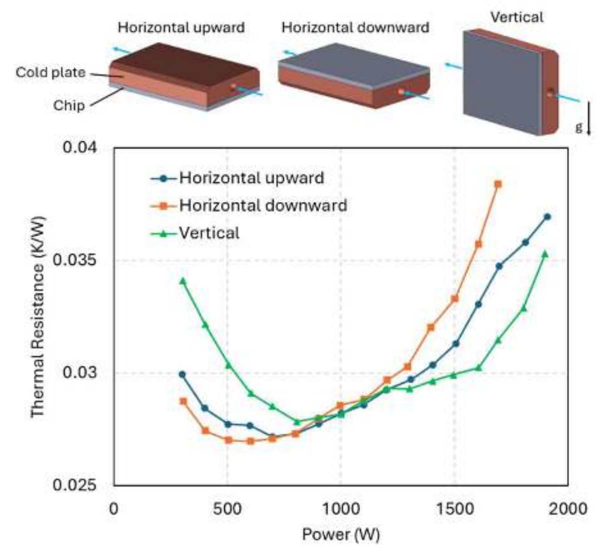

Fig. 2 Thermal resistance of a cold plate under different orientation conditions.

nucleate boiling, occurring at a vapor quality range of 0.2~0.6. The following increase of thermal resistance with power at high power range is due to the increasing vapor quality (>0.7 at 1500 W) causing departure from nucleate boiling.

Comparing the three orientations, the thermal resistance exhibits different trends at different power ranges. At low power below ~800 W, the vertical orientation shows the highest thermal resistance and the horizontal downward orientation shows the lowest thermal resistance among the three. At high power above ~1200 W, the trend is completely opposite. Although the cold plate is working under flow boiling mode and gravity is not expected to play a major role, the difference between them can still be attributed to the different distribution of flow and movements of bubbles due to buoyancy.

At low power, bubbles are sparsely generated with a small number density. Since vapor phase possesses lower density, the horizontal downward orientation tends to keep the bubbles on the heated wall, ensuring enough liquid-vapor interface existing near the wall for efficient evaporation. Conversely, the bubbles tend to rise and leave the wall for horizontal upward orientation, and the wall is covered with mostly liquid, yielding lower heat transfer coefficient than horizontal downward orientation. The vertical orientation shows the worst thermal resistance, which likely results from the maldistribution of fluid flow due to gravity, as the flow tends to stratify with vapor at the top and liquid at the bottom when bubble behavior at low power could not provide sufficiently violent turbulence. On the contrary, at high power, bubbles are densely populated after boiling is fully developed. The horizontal downward orientation pins the bubbles to the wall, causing them to coalesce and form vapor films, deteriorating heat transfer; while the bubbles depart the surface more freely for horizontal upward orientation, resulting in comparatively lower thermal resistance. The vertical orientation yields the highest performance under high power, which is likely due to the vertical bubble departure movements sweeping over the heated surface and enhancing convection.

All orientations offer high thermal performance despite the slight differences discussed above. The case-to-fluid thermal resistance was kept below 0.03 K/W at 1200 W. Tests with a higher flow rate of ~750 mL/min further showed similar low thermal resistance up to 2000 W, which is enabled by the lowered vapor quality below 0.6 preventing heat transfer deterioration. The low thermal resistance at these extreme high-power conditions, especially with a small heated area (corresponding to heat fluxes >200 W/cm^2), demonstrates the ability of two-phase cooling as an efficient thermal management method for future generations of high-power processors, which can be packaged in any designed orientations.

IV. Conclusion

In order to increase rack, server, and chip level thermal performance, two-phase cold plates operating in vertical and horizontal downward (opposite orientation of common cold plates) orientations are being investigated and requested by the thermal packaging community. A feasibility thermal test was performed to demonstrate and compare the capability of direct-to-chip two-phase cold plates in these abnormal orientations. The effect of orientation on performance varied depending on the orientation. At lower power and lower heat flux conditions, horizontal downward cold plates performed better than standard horizontal upward oriented cold plates. At higher powers, vertical cold plates outperformed horizontal upward cold plates. At all power conditions and orientations, no substantial dry-out or performance degradations were noticed, indicating the direct-to-chip two-phase solutions can be considered in any orientation.

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