High-Heat-Flux Rack Level Direct-to-Chip Two-Phase Cooling Using Sustainable Fluids

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Abstract—**Data centers continue to increase power density, with direct-to-chip two-phase cooling seen as one potential technology capable of displacing air cooling. However, legacy refrigerants used in direct-to-chip two-phase cooling, such as R134a, have high global warming potentials (GWPs). R134a's GWP is over 1,300. This paper experimentally compares the performance of R134a with R1336mzz(Z) (a refrigerant with a GWP of 2) in a representative 20kW rack level test. Overall, the thermal performance of R1336mzz(Z) was lower than R134a when dropped into a direct-to-chip two-phase cooling system that was optimized for R134a. Although the performance was lower across the range of conditions tested, the performance of R1336mzz(Z) was still excellent, capable of cooling current high-performance CPUs and potentially next-generation GPUs. Considering the high thermal performance of R1336mzz(Z) and its inherently low global warming potential, further consideration of R1336mzz(Z) as a direct-to-chip two-phase-cooling working fluid in a cooling system optimized for R1336mzz(Z) is warranted.**

Keywords—data center cooling, direct-to-chip two-phase cooling, low global warming potential refrigerants, high-heat-flux thermal management

I. INTRODUCTION

The increased power densities in data centers created by emerging technologies such as artificial intelligence and machine learning, has pushed the limits of air cooling. Two-phase cooling technology has the potential to meet the increased power density requirements. Two-phase cooling with mini-channels has shown heat flux removal capabilities of over 183W/cm^2 [1]. Capillary based two-phase cooling has demonstrated heat flux removal capabilities over 970W/cm^2 [2]. Researchers have also incorporated micro-channels directly into the integral heat spreaders of CPUs, removing over 1,000W at temperature differences less than 50K [3,4]. However, the working fluids used in these studies possess high GWP. Recently, R1336mzz(Z) has seen interest as a low GWP cooling fluid. Li et al., have investigated the use of R1336mzz(Z) for immersion cooling of batteries [5]. Kedzierski and Lin performed pool boing tests on reentrant cavity surfaces [6]. Presented in this paper are experimental two-phase cooling data using R134a and R1336mzz(Z) in a rack level test. The experimental data shows the more sustainable R1336mzz(Z) fluid to have thermal performance lower than R134a (a high GWP fluid) but still sufficient to meet the increasing demands of the high-power data center cooling market.

II. EXPERIMENTAL SETUP

A thermal test vehicle (TTV) was developed to allow the testing of sleds with two CPUs. Each simulated CPU provided the capability to closely simulate the performance of the Intel Saphire Rapids package. This was accomplished by using 4 appropriately located ceramic heaters and an integral heat spreader. The case-to-fluid thermal resistance of the TTV was then calibrated with an Intel-supplied TTV. The ceramic heater packages were each capable of delivering 250W at a heat flux of 250W/cm^2. Type T Thermocouples were placed in several locations within the TTVs. Two thermocouples were placed along the centerline of the TTVs, between the heat sources. Those thermocouples were used to measure the temperature values that were then used to calculate the measured case-to-fluid thermal resistances. Thermocouples were also used to measure the temperature at the center of the heat sources. These temperature values were used to calculate the overall heat transfer coefficient of the evaporators. The saturation temperature of the system was also measured using thermocouples placed along the wall of the loop exiting the evaporators. The rack further consisted of 12 sleds, (each with 2 CPUs), pumps, manifolds, fluid reservoirs, and a flat plate heat exchanger coupled to a chiller for ultimate heat removal. Shown in Fig. 1 is a photograph of a sled complete with TTVs and the rack described above.

III. TEST RESULTS

A test was performed to measure the performance of micro-channel evaporators in a rack with the sleds plumbed in parallel. Eleven of the sleds were powered constantly with a power of 1,000W per sled (500W per CPU). One sled (from which our results are reported) was applied variable power, with the power on each CPU ranging from 0 to 850W (in approximately 50W increments). The pumping power was also kept constant throughout the test. It is estimated that the vapor quality at the exit of the evaporator was approximately 0.7 when operating at 850W. The 500W evaporators had an exit vapor quality of approximately 0.4.

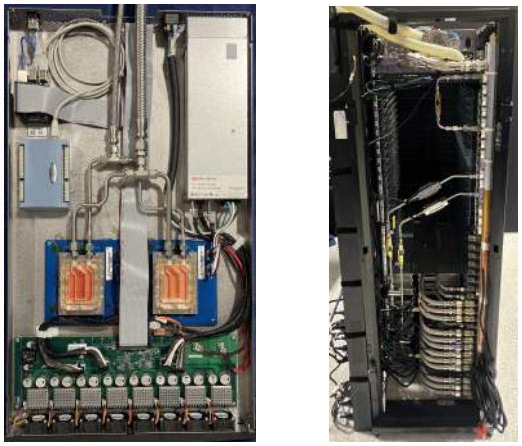

Fig. 1. Photograph of sled with two CPU test vehicles, evaporator plates, plumbing, power modules, and instrumentation (Left). Photograph of Rack populated with 12 Sleds, manifolds, and pump control unit.

An initial test was done with R134a (as described above) with the chiller set to a constant inlet temperature of 298.15K.. The cooling system was then drained and replaced with R1336mzz(Z). Fig. 2 shows a plot of the case-to-fluid thermal resistance measured during both of those tests. The reported case-to-fluid thermal resistances were calculated using a procedure recommended by Intel. Overall, the thermal resistance of R134a was lower across all power levels. However, the thermal resistance measured with R1336mzz(Z) was still sufficient for the majority of the range. From 470W to 770W, the case to fluid thermal resistance was less than 0.03K/W, which is lower than most high-performance single-phase liquid solutions. Fig. 3 shows the average overall heat transfer coefficient as measured at the center of each heat source on the TTVs. Here, the overall heat transfer coefficient is defined using the measured surface temperatures of the TTV, the average bulk temperature of the fluid above the heat source, and the heat flux of the heat source. The thermal resistance associated with the thermal grease, conduction through the base and fins of the evaporator, and the two-phase convective thermal resistance are all included. Although R1336mzz(Z) was lower than R134a across the range of heat flux tested, the maximum measured heat transfer coefficient above 90,000W/m^2-K using a cooling system that was not optimized for it, is noteworthy. The performance of R134a was also excellent when considering that the exit vapor quality of approximately 0.7 insinuates a rather economical liquid flow rate was used to obtain these results.

IV. DISCUSSION

The thermal performance of R1336mzz(Z) as a drop-in replacement fluid for R134a was lower in a two-phase direct-to-chip 20kW rack-level demonstration. However, considering the relatively high performance demonstrated and favorably low GWP (2 versus over 1,300), further consideration of R1336mzz(Z) is highly recommended. As a next step, it is recommended that a direct-to-chip two-phase cooling system optimized for R1336mzz(Z) be designed, fabricated, and tested. Considering that R1336mzz(Z) has substantially lower saturation pressure (more than 8 times lower at 308.15K), it is expected that the channel sizes will need to be increased to minimize vapor velocities and any associated pressure drop penalties within the system.

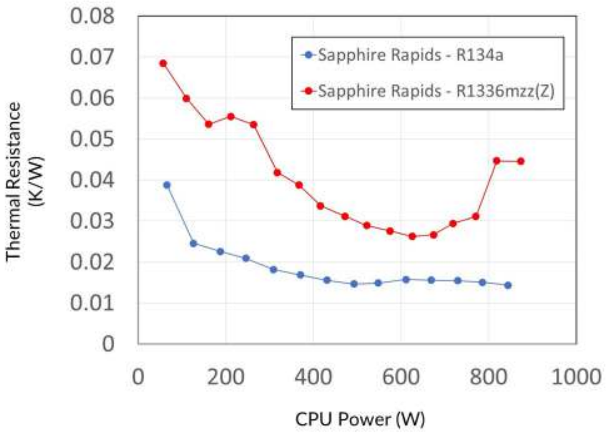

Fig. 2. Plot of measured case to fluid thermal resistance for an Intel Sapphire Rapids TTV using R134a and R1336mzz(Z) as the working fluid.

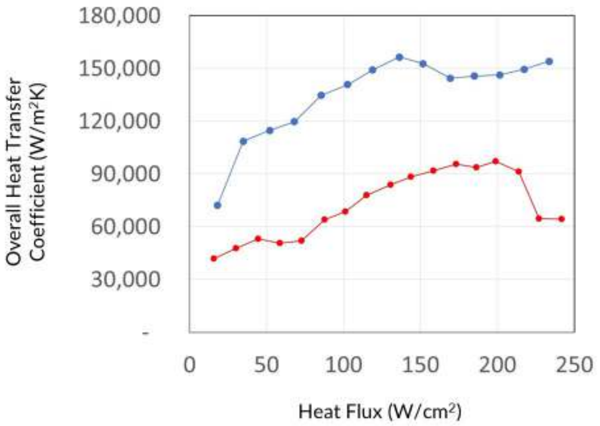

Fig. 3. Plot of the overall heat transfer coefficients acquired using R134a and R1336mzz(Z) as the working fluids.

ACKNOWLEDGMENT

The authors thank Tyler Richardson and Brendan Mahany for supporting fabrication and testing efforts. Special thanks to Chemours for providing the R1336mzz(Z) (Opteon™ SF33) fluid used in this study.

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