# Experimental Characterization of a Server-Level Thermosyphon for High-Heat Flux Dissipations

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## ABSTRACT

This paper advances the work presented at ITHERM 2019 in which a novel thermal technology has been introduced to cool servers and datacenter racks more efficiently compared to the traditional air-based cooling solutions. As reported in the state-of-the-art and the previous papers published by the same authors, heat flux dissipation in telecom servers and high-performance computing servers is following an exponentially increasing trend in order to handle the new requirements of higher data transmission, data processing, data storage and massive device connectivity dictated by the next industrial revolution. This trend translates into the need for upgrading the capacity of existing servers and datacenter racks, as well as building new datacenters around the globe. The envisioned cooling technology, which will improve datacenter energy usage, is based on a novel combination of low-height thermosyphons operating in parallel to passively dissipate the heat generated by the servers and rack-level thermosyphons equipped with an overhead compact condenser, to dissipate the total power from the server rack to the room-level water cooling loop.

The present paper is mainly focused on the experimental evaluation of the thermal performance of a 7-cm high liquid-cooled thermosyphon designed to cool a 2-U server with a maximum heat dissipation here of 200 W (but could have gone even higher) over a 4 x 4 $cm^2$ pseudo-chip footprint. A new test setup and filling rig were designed at Nokia Bell Labs in order to accurately evaluate thermosyphon thermal performance over a wide range of heat loads, secondary side mass flow rates and inlet temperatures, using R1234ze(E) as the working fluid. A new extensive database was obtained, capturing the entire thermosyphon characteristic curve, expressed as total thermal resistance as a function of the power. Here, the experimental results are presented and discussed in detail, and they demonstrate that passive two-phase thermosyphon-based approach provides significant advantages in terms of cooling performance, energy efficiency and noise level compared to other datacenter cooling solutions available on the market or under development.

**KEYWORDS:** Datacenters, experimental study, passive cooling, R1234ze(E), servers, thermosyphon, two-phase flow.

## NOMENCLATURE

| | |
|---|---|
| D | depth, (m) |
| d | diameter, (m) |
| L | length, (m) |
| m | mass flow rate, (kg/s) |
| P | pressure, (Pa) |
| Q | heat load or power dissipation, (W) |
| R | thermal or electrical resistance, (K/W) or (Ω) |
| T | temperature, (K) |
| W | width, (m) |
| | **Greek symbols** |
| Δ | difference between two quantities, (–) |
| ρ | density, (kg/$m^3$) |
| | **Subscripts** |
| evap | evaporator |
| heaters | cartridge heaters |
| in | inlet |
| mean | mean |
| sh | shunt |
| sub | subcooling |
| th | thermal |
| therm | thermosyphon |
| thermocouple | thermocouple reading (K-type) |
| thermometer | thermometer reading (Pt-100) |
| w | water |
| | **Acronyms** |
| CDU | Cooling Distribution Unit |
| CPU | Central Processing Unit |
| CRAC | Computer Room Air Conditioning |
| CRAH | Computer Room Air Handling |
| GWP | Global Warming Potential |
| PCB | Printed Circuit Board |
| RAM | Random Access Memory |

## CONTEXT

Data transport, processing and storage are following an exponentially increasing trend, driven by higher demands in mobile broadband, video and gaming, cloud computing, 5G networks and Internet of Things (IoT). Such escalating trends are directly linked to the next-generation digital transformation, which will be dominated by intelligent machine-to-machine and human-to-machine communications, as well as massive device connectivity automating everything everywhere [1]. This will have profound implications on overall system design with the associated general trend being towards highly integrated devices/components and thus achieving greater functionality per unit volume. Integration is required for cost, space and efficiency and has to occur over a wide range of length scales, going from μm/mm of the chip/package-scales to hundreds of meters of datacenter-scale (the latter is the focus of this paper).

As our reality is moving from physical to virtual, more and more organizations require datacenters in their business for colocation services, cloud solutions, compliance assurances, and other services. Consequently, it is expected that the number of datacenters is expected to grow significantly within the next two to five years. Currently, 90% of datacenters worldwide are air-cooled using different implementations (i.e. free cooling, raised floor cooling, hot-aisle/cold-aisle containment cooling system, etc.). Depending on the operating conditions, more than 50% of the total energy consumption of a datacenter is dedicated to cooling due to the necessity of CRAC/CRAH units, room-level blowers and server-level fans to continuously circulate the cold air in the racks to keep the temperatures of the IT equipment and auxiliary components within the standards. Therefore, with many new datacenters and upgrades of existing ones on the horizon to meet consumer and 5G needs, the harsh reality is that datacenter electrical energy consumption may increase in the future (after 2021) and have significant negative enviromental consequences. Even though developments in datacenter energy efficiency over the last decade have avoided reaching unsustainable energy demands, innovative thermal management technologies need to be introduced in order to improve the efficient and sustainable use of energy in the current and next-generation datacenters [2-4].

## ENVISIONED COOLING TECHNOLOGY

The core of this cooling technology is represented by the implementation of passive gravity-driven two-phase flow, using a dielectric and environmentally-friendly refrigerant, implemented as thermosyphons to address heat transfer at both the server-level and rack-level in datacenters.

In general, a thermosyphon loop is composed of four main components (evaporator, condenser, riser and downcomer), as explained in detail in [5-7] and shown in Fig. 1. The heat is transferred from the evaporator (hot side) to the condenser (cold side), and these two components are connected via riser and downcomer tubes. In order to ensure passive flow circulation, the system driving force needs to be higher than the total pressure drop over the entire range of operating conditions. The driving force (often called gravitational pressure gain) is proportional to the height of the thermosyphon and the $\Delta\rho$ between the subcooled liquid flowing downward by gravity force in the downcomer and the saturated two-phase mixture flowing upward by buoyancy force in the riser.

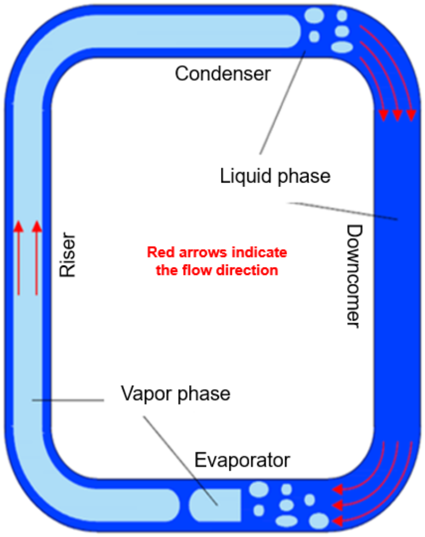


Figure 1 – Thermosyphon flow loop schematic indicating the locations where liquid and vapor are present and the direction of the flow. Here there is the assumption that the boiling process in the evaporator (and condenser) goes through different flow regimes (i.e. subcooled liquid, bubbly flow, slug-plug flow and fully annular flow). Naturally, in the real operations the flow regimes in the system depend on the power delivered to the refrigerant flow, filling ratio and system geometry.

The key characteristics to design a thermosyphon cooling loop are: *(i)* the evaporator has to be installed below the condenser as this is a gravity-driven system; *(ii)* the evaporator has to be properly sized as it is the main driver of the system, generating the buoyant vapor by removing heat from the target component(s); *(iii)* the control of the system pressure, and thus the temperature at which boiling occurs, by the secondary side coolant inlet temperature; *(iv)* the characterization of the dry-out for a given geometry and working fluid (refrigerant) in order to have stable thermal performance and a scalable cooling system toward high power dissipations.

The future of datacenter cooling is represented by passive two-phase flow and the implementation proposed by the authors is illustrated in Fig. 2. The proposed cooling technology operates with numerous server-level thermosyphons operating in parallel in order to dissipate the heat generated by the large heat sources of the 20-40 servers (CPUs, hard drives, RAMs, etc.) of a rack simultaneously (server-level cooling is the main focus of this paper). Then, the heat is transferred to one or more rack-scale thermosyphons via intermediate heat exchangers, which have one or more overhead compact condensers (located on the top of the server rack) for dissipating the total power of the server rack to the room-level water cooling loop (20-100 kW or more per rack). Additionally, thanks to the low thermal resistance of the cooling system, the water can operate at high capture temperatures becoming a very profitable free source of thermal energy to re-use within a district heating network or to preheat boiler feed water in a power plant, or in other waste heat recovery applications [8].

As mentioned earlier, air-based cooling using the conventional hot-aisle and cold-aisle containment systems will require huge energy requirements for the next-generation power demands, therefore a shift has already begun in datacenters towards more advanced liquid-cooling systems. These can be mainly classified in four categories: direct water-based cooling using micro-channel evaporator cold plates, single-phase immersion cooling using mineral oils, active/passive two-phase immersion cooling using dielectric fluids (i.e. Novec HFE-7000, 7100, etc.) and room-level two-phase modular cooling. Even though these solutions are more efficient than air-cooling implementations, they still present significant implementation challenges to be able to be classified as long-term, viable technologies for datacenter cooling as discussed in [10].

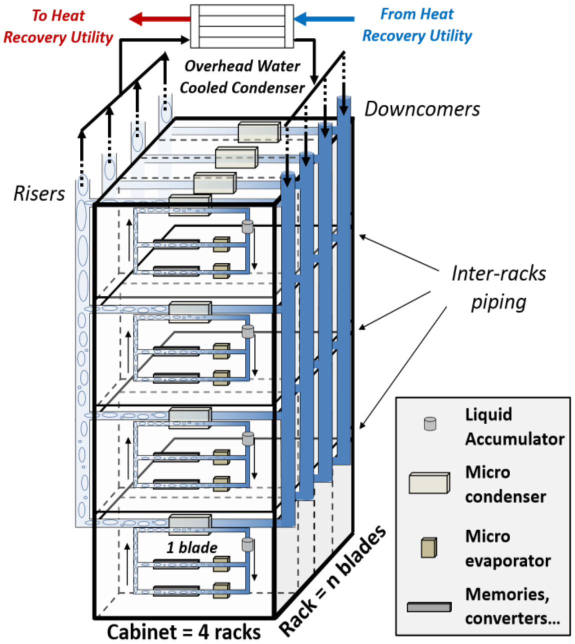


Figure 2 – Passive two-phase cooling technology for next-generation datacenters, as presented by Szczukiewicz et al. [5] and Amalfi et al. [9]. The schematic reports a server rack fully populated with blade servers (vertical orientation), but this approach can be easily applied to pizza box-type servers (horizontal orientation). The authors have already proved that passive two-phase cooling can be properly designed for multiple scales, going from the large heights of the telecom units (50-120 cm) [6] to the small heights of compact servers as demonstrated in this study. The details regarding the geometry of the server-level and rack-scale thermosyphons, as well as the overhead condenser and mechanism to ensure "hot swappable" servers are not disclosed as they are confidential.

The cooling technology reported in Fig. 2 provides many advantages that overcome all challenges related to existing or under development cooling solutions, among which are: *(i)* passive two-phase heat removal from server-to-rack-scale along with a significant reduction in server-level fans, air movers/blowers and CRAC/CRAH units; *(ii)* projected lower first costs, reduce complexities and space requirements associated with a CDU for liquid-cooling distribution; *(iii)* higher heat transfer effectiveness on the heat rejection side thanks to the optimized design of the overhead condenser to a liquid-cooling loop and lower thermal resistance due to the use of passive two-phase cooling; *(iv)* modular system design suitable for standard and non-standard applications coupled with the possibility of having "hot-swappable" servers for maintenance and components' upgrade; *(v)* environmentally-friendly technology by using nearly zero-GWP refrigerants, such as R1234yf, R1233zd and R1234ze(E), the latter has been used in the present experimental study and there is a plan in the near future to test the other fluids.

## EXPERIMENTAL SETUP AND CALIBRATIONS

Based on the implementation reported in Fig. 2, the goal of this study is to address the heat transfer process at the server-level, while the analysis of rack-level thermosyphons and overhead condenser will be investigated as a next step. Figure 3 shows the experimental setup built at Nokia Bell Labs, where the main components are:

- A 7-cm high micro-thermosyphon for server-level cooling in which the evaporator extracts the heat from a pseudo-chip and the condenser rejects the heat to a secondary side water-cooling loop. The external dimensions of the thermosyphon components are reported in Table 1. A Schrader valve is located on the downcomer line for vacuum and pressure tests, as well as for charging and discharging operations. The server-level thermosyphon was simulated by JJ Cooling Innovation and fabricated by Provides Metalmeccanica;

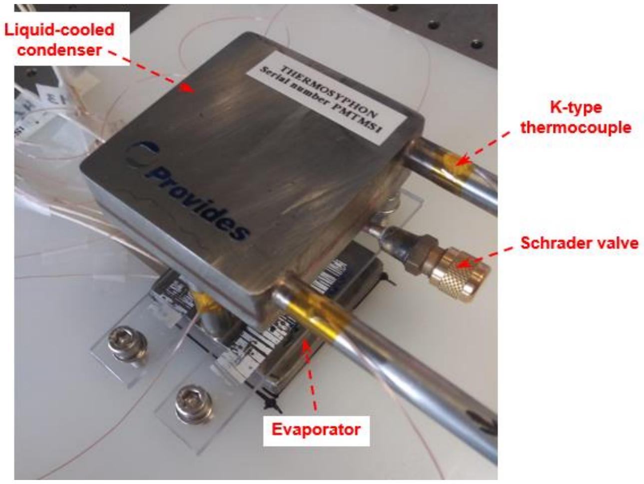
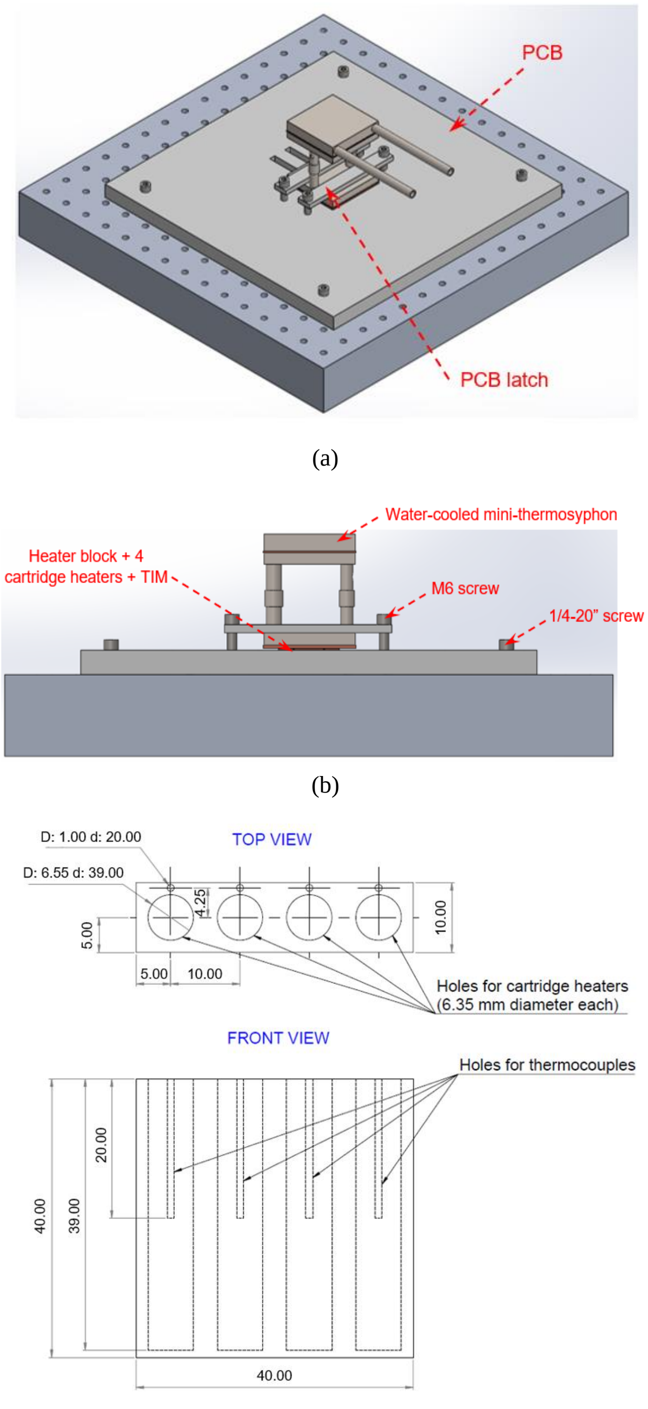


Figure 3 – Experimental setup built at Nokia Bell Labs and close view of the server-level thermosyphon before putting the insulation material to minimize the heat loss through the ambient. The evaporator is directly attached on the pseudo-chip (footprint area 4 x 4 $cm^2$) via a highly conductive thermal grease with a thermal resistance of 0.0032 K/W (defined by the manufacturer). The secondary side of the condenser is cooled by water at a given mass flow rate and inlet temperature using a thermal circulation bath.

Table 1 – External geometry of the server-level thermosyphon

| COMPONENT | DIMENSIONS |
|---|---|
| Evaporator, L / W / D | 60 / 60 / 9.50 mm |
| Condenser, L / W / D | 60 / 60 / 18.50 mm |
| Riser, L / d | 42 / 10 mm |
| Downcomer, L / d | 42 / 8 mm |
| Secondary side tubes, L / d | 100 / 8 mm |

- A pseudo-chip that is composed of 4 parallel cartridge heaters embedded within a copper block providing a maximum power dissipation of about 330 W. Two PCB latches are used to ensure the proper contact pressure on the thermal interface material (located between the pseudo-chip and the base of the evaporator) to minimize the total thermal resistance as reported in Fig. 4;



(a)

(b)

(c)

Figure 4 – Schematic of the test setup: (a) drawing showing the overall system and in particular the PCB and the two latches; (b) drawing highlighting the thermosyphon and the heater block underneath; (c) detailed geometry of the copper block for the four cartridge heaters.

- An electrical circuit including the connections of the cartridge heaters to the power supply and to the DAQ in order to measure the effective input power (see Fig. 5);

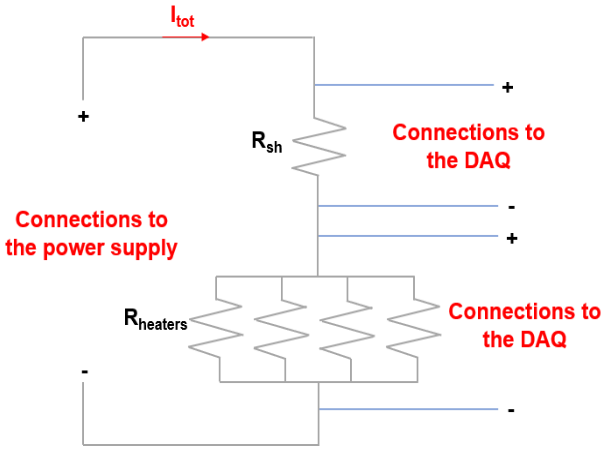
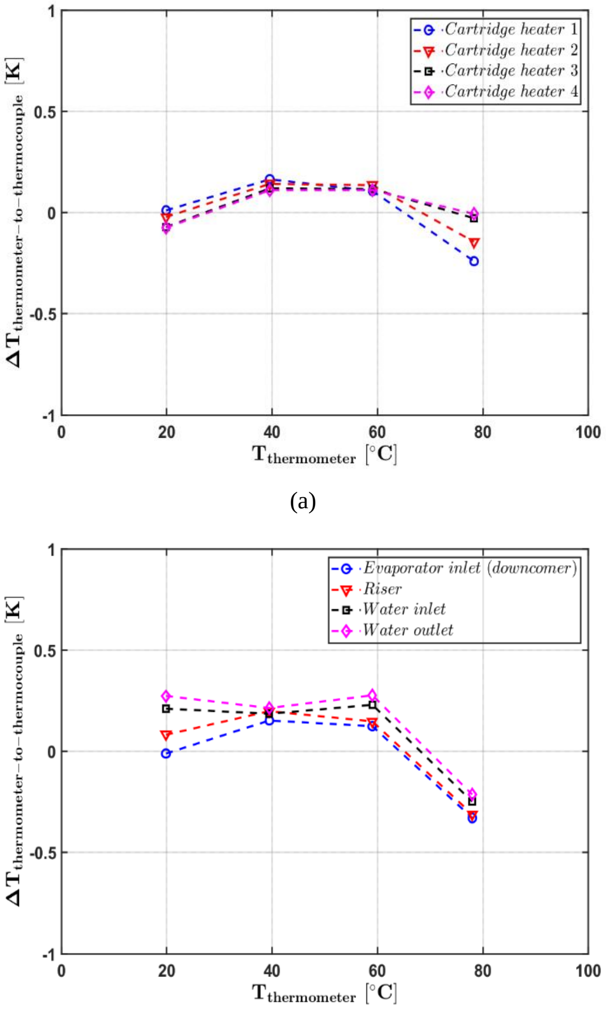


Figure 5 – Schematic of the electrical circuit that connects a shunt resistor with four Omega cartridge heaters in parallel. The voltage across the shunt is measured to calculate the current flowing into the circuit by knowing its resistance (1 Ω). Then, the equivalent resistance for the four heaters is measured as voltage divided by current and correlated with the operating temperature during a dry (conduction test). During the formal experiments, the effective power delivered to the refrigerant flow is calculated by computing the multiplication between the equivalent resistance and square of the electrical current.

- A thermal circulation bath is installed to supply water on the secondary side of the condenser at a given flow rate and inlet temperature. The condenser of the server-level thermosyphon operates in a counter-flow arrangement;
- A charging station (not shown in Fig. 3) to fill the system with R1234ze up to the desired value of filling ratio. This is defined as the ratio between the initial volume of the liquid refrigerant at a reference temperature divided by the total internal volume of the system (filling ratios are confidential information, so not disclosed here);
- Eight K-type thermocouples are installed to evaluate the thermal performance of the server-level thermosyphon. In particular, four thermocouples are inserted in the copper heater block to calculate the mean junction temperature by taking into account one-dimensional heat conduction through the copper block and thermal interface material. Two thermocouples are located at the inlet of the evaporator and in the adiabatic section of the riser to measure the fluid temperature and system pressure respectively. Then, the last two thermocouples are used to measure the inlet and outlet temperatures of the water cooling loop and to calculate the water flow rate via a single-phase energy balance for a given input power. The server-level thermosyphon thermal resistance is calculated as the ratio of the temperature difference between the junction and the water inlet temperatures to the total power dissipation. All thermocouples were in-house calibrated over a temperature range going from 10 °C to 80 °C in order to

reduce the uncertainty of the measurements from ± 1.00 °C (given by the manufacturer) to about ± 0.25 °C. The validation results of the calibration procedure are reported in Fig. 6;



(a)

(b)

Figure 6 – Validation of the thermocouple calibration expressed as the temperature difference between the reference thermometer and the thermocouple reading as a function of the thermometer reading (Pt-100). The results show an average accuracy of the K-type thermocouples equal to about ± 0.25 °C: (a) thermocouples 1 to 4 are used to measure the temperatures of the cartridge heaters (acquisition channels 1-4); (b) thermocouples 5 to 8 are used to measure fluid temperature, saturation temperature and secondary side inlet/outlet water temperatures (acquisition channels 5-8).

- A data acquisition system controlled by a LabView program is used to set the operating conditions and to monitor the thermal performance over time. Once steady-state is reached, the data acquisition system starts scanning all channels (frequency of 25 Hz); the measured parameters (i.e. temperatures, power, etc.) are averaged over 1 minute and analyzed later by another program written in Matlab. It has to be mentioned that a range between 10 and 15 minutes is needed to reach the steady-state condition. The latter is determined based on the standard deviation of the temperature measurements that is set to ± 0.25 °C. The uncertainity of the input power and total thermal resistance (min. and max.) are ± 0.90%, and ± 1.34-5.89% respectively (based on Kline and McClintock [11]).

## EXPERIMENTAL RESULTS

In this study, the cooling capabilities of the server-level thermosyphon are presented under steady-state conditions. The results reported in Figs. 7 to 10 refer to a fixed water inlet temperature of 15°C, R1234ze as the working fluid, a range of power dissipations going from 5 W to 200 W and three water mass flow rates of 364, 397 and 460 kg/h. During the passive two-phase tests, the maximum base heat flux is 12.5 W/cm$^2$ (calculated according to the copper heat block area of 4 x 4 cm$^2$), while the footprint heat flux (at the smaller fin area base of 3.5 x 3.5 cm$^2$) is 16.3 W/cm$^2$. R1234ze is selected as the working fluid since it is a very promising fluid for electronics cooling applications due to its favorable thermodynamic properties and negligible environmental impact, and therefore is considered one of the best candidates to replace the existing R134a [12]. Moreover, datacenter water (no need for high purity water) at high flow rates is used on the heat rejection side of the server-level thermosyphon to minimize the secondary side thermal resistance, and thus to reproduce the operating conditions of the complete cooling implementation (see Fig. 2), where the intermediate heat exchangers operate in a condensation-to-boiling flow configuration. Furthermore, the results in Figs. 7 to 10 show that the secondary side water mass flow rate has a negligible effect on the system thermal performance (data points are within the accuracy of the measurements). This can be justified by the fact that the condenser overall heat transfer coefficient is mainly controlled by the primary side thermal resistance, corresponding to the condensing side of the server-level thermosyphon.

Figure 7 illustrates the total thermal resistance as a function of the power which also includes the contributions of the thermal interface material, evaporator and condenser. Conduction thermal resistance plays a negligible role as passive two-phase cooling is triggered at very low powers (3-5 W).

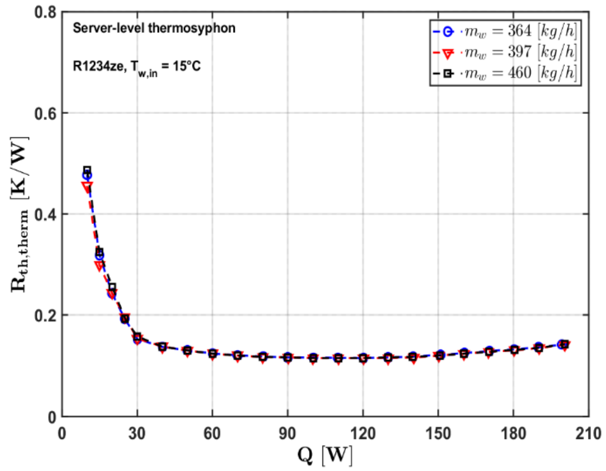


Figure 7 – Thermosyphon (total) thermal resistance as a function of the power for three different water mass flow rates.

Overall, the total thermal resistance decreases with increasing the power dissipation due to the enhancement in the boiling process (higher refrigerant mass flow rates, heat fluxes and vapor qualities). The change in thermal resistance slope at about 30 W indicates a clear transition in the two-phase flow regime evolving in the thermosyphon which enhances the thermal performance. The minimum value of thermal resistance is measured to be 0.113 K/W at a power level of 120 W.

The mean junction temperature (see Fig. 8) increases with power dissipation, reaching a maximum value of 43°C (for a water inlet of 15°C) that is far below the values obtained with traditional air-cooling technologies (cold aisle/hot-aisle containment cooling, plus air-cooled heat sinks at the server-level). This means the inlet water temperature could easily be raised 55°C or higher to dissipate this heat to the environment.

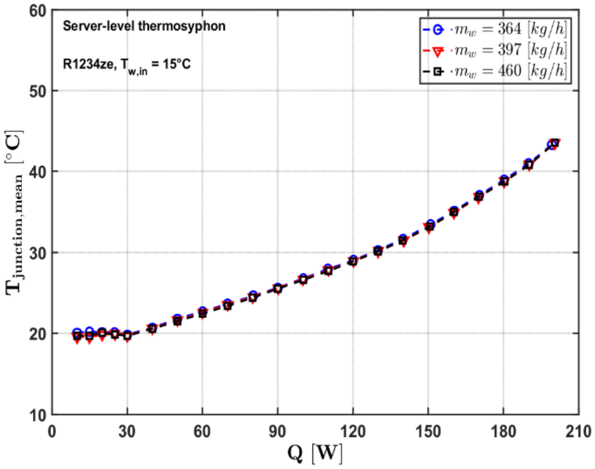


Figure 8 – Mean junction temperature of the pseudo-chip as a function of the power for three different water mass flow rates.

It is interesting to notice that Amalfi et al. [13] presented a thermal performance analysis of a 2-U air-cooled server HP ProLiant DL 180 G6 in which a similar value of junction temperature (around 45 °C) was obtained only when the server-level fans operated at the maximum flow rate. At this condition, the fan power consumption was 120 W, corresponding to more than 20% of the total server power dissipation. The proposed approach using thermosyphons coupled with a little air flow circulation within the servers will: (i) reduce the number of fans, potentially translating into more compact servers with less costs and less noise; (ii) solve the inevitable problem of non-uniform cooling of multiple CPUs operating in parallel; (iii) provide at least a 10-fold reduction in energy consumption, therefore much lower costs to operate datacenters with the possibility of easily upgrading the CPUs without substantial changes of the cooling system and being green to the environment.

Figure 9 depicts the trend of the internal pressure of the server-level thermosyphon, which increases with the power, reaching a maximum value of 5.8 bar at 200 W. It has to be pointed out that formal experiments were stopped at 200 W to preserve the integrity of the prototype and not because the thermosyphon had reached its maximum heat removal capability. Indeed, thermal design simulations suggest that the present thermosyphon can dissipate up to 250 W without going into the undesired frictional dominant regime [14]; this is equivalent to a base heat flux of 15.6 W/cm$^2$ and a footprint heat flux of 20.4 W/cm$^2$, and this is still not the critical heat flux.

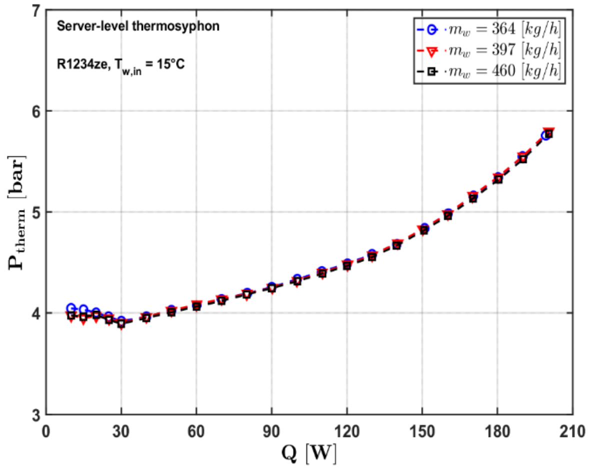


Figure 9 – Thermosyphon internal pressure as a function of the power for three different water flow rates.

Figure 10 shows the subcooling of the liquid refrigerant before entering the evaporator as a function of the power dissipation. Based on the passive two-phase operating principle of a thermosyphon, the subcooling has to increase with the amount of power removed from the heat source since more liquid is stored in the downcomer (higher liquid head). As can be seen from the experimental trend, the maximum subcooling is 9.3 K at 200 W power dissipation without adversely influencing operation.

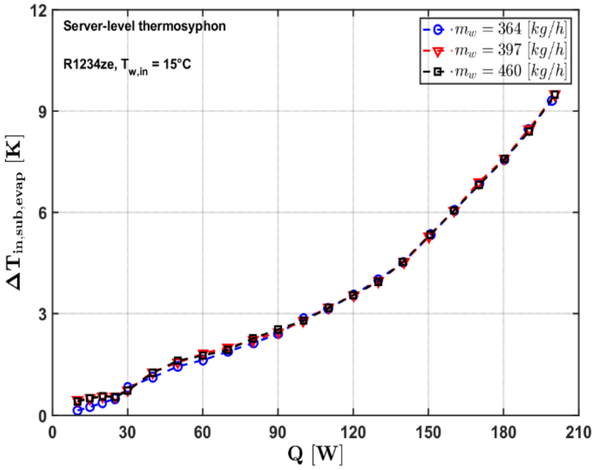


Figure 10 – Subcooling measured at the inlet of the evaporator as a function of the power for three different water mass flow rates.

Figure 11 presents the total thermal resistance of the server-level thermosyphon as a function of the secondary side water inlet temperature for three different power levels: 20, 40 and 60 W. As the inlet temperature of the water increases from 10 °C to 30 °C, the thermal resistance decreases with a gain in cooling capability, mainly due to the lower density difference between the liquid and vapor phase which provides lower pressure drop for the passive flow circulation

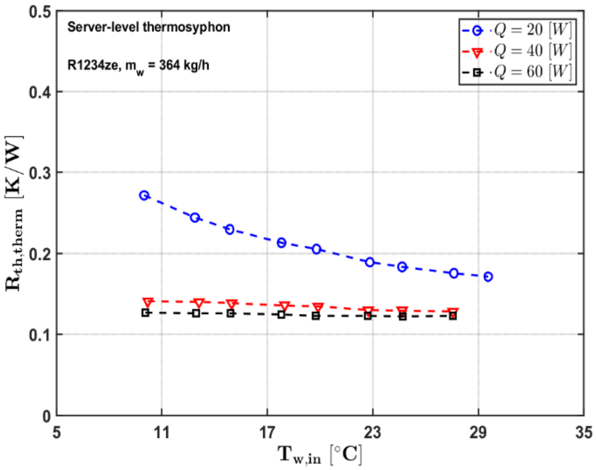


Figure 11 – Thermosyphon (total) thermal resistance as a function of the water inlet temperature for three different power dissipations. Experimental data for the water inlet temperature of 30 °C and for the power levels of 40 and 60 W were not acquired as the internal pressure of the thermosyphon would have achieved values greater than 6 bar (beyond our safety limit linked to the present fabrication process).

## CONCLUSIONS

This paper continues the work presented at ITHERM 2019 on the importance of developing novel cooling technologies for curbing the acceleration of datacenter energy use. The present work gives an overview of a novel thermosyphon-based technology that aims to address the heat transfer at the server-level and rack-level using passive two-phase flow. In particular, low-height thermosyphons are used to dissipate the heat from the servers (i.e. CPUs, hard drives, RAMs, etc.) and transfer it to rack-level thermosyphons that are designed with an overhead compact condenser located on top of the server rack. This component rejects the total power of the rack to a facility-level liquid-cooling loop (20-100 kW or more per rack).

The main goal of this paper is to perform an experimental study to characterize the cooling capability of a thermosyphon in which the total height from evaporator to condenser is only 7 cm and is suitable for the cooling of 2-U servers. A novel test setup was built at Nokia Bell Labs and the thermal performance of the new prototype is tested over a wide range of operating conditions using R1234ze as the working fluid. Experimental results are presented in detail, including the trends of total thermal resistance, mean junction (pseudo-chip) temperature, system pressure and evaporator inlet subcooling as a function of power dissipation (5 to 200 W), secondary side water inlet temperature and mass flow rate. Furthermore, the results demonstrate excellent thermal performance and stable cooling with a minimum thermal resistance of 0.113 K/W at 120 W. The proposed passive two-phase cooling technology will enable efficient cooling of next-generation high-power datacenters, being scalable, using environmentally friendly refrigerants and resulting in high energy capture and low noise levels.

As future work toward the complete development of this cooling technology, the authors will: (i) design, fabricate and test a new server-level thermosyphon able to dissipate up to 300 W per heat source and reach higher internal pressures; (ii) characterize experimentally the thermal performance of the new prototype as a function of different refrigerant charges and working fluids (i.e. R1233zd, R1234yf, etc.); (iii) advance the design and testing of the rack-scale thermosyphon, including the overhead condenser; (iv) develop unique simulation tools to design passive two-phase cooling system for individual servers or for an entire server rack based on the experimental data gathered during this project.

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