Orchestrating a brighter world NEC

NEC Direct Liquid Cooling Technologies

Contents

History

The technology of using liquids for cooling computer hardware has been around for a few decades. The first machines in the supercomputer-class employed an immersive cooling technique with Freon as the coolant. The chips were often implemented in ECL technology (Emitter Coupled Logic), which allowed the highest clock frequencies but required high power as well.

This type of Immersion Cooling (IC) made it difficult to perform hardware service on such a machine, since the coolant had to be drained first.

There is currently a renaissance of IC for servers. These approaches often employ a two-phase liquid, which turns from the liquid into the gaseous state when in contact with hot components

The mainframes of the early 1980s also pioneered liquid cooling for the main processor chips, which were packaged in a highly integrated module, using water as the cooling liquid. This technology is the forerunner of today's Direct Liquid Cooling (DLC, synonymous to DCLC, for "Direct Chip Liquid Cooling") technology.

The Problem with Air Cooling

It is common now for server processors to have a TDP range of up to 300 W. This value is already a problem for air cooled high density "2U4N" servers in the popular 2U (rack units) chassis format with four motherboard trays (nodes) inside. The high integration density of the components leaves only a small volume available for cooling fans. Accommodating processors with 240 W requires lower air-intake temperatures, so the air-cooling is still feasible at all.

The processor manufacturers aim for designs with 300 W TDP and above, so air-cooling in a 2U4N server will no longer be possible. The main reason for this is the fact that the fan power increases with the third power of the volumetric flow rate, as stated in the "third fan law". In a rough estimate, this means that if processors with 300 W TDP are used instead of processors with 200 W TDP, the fan power will have to increase by a factor of 3.4. A typical 2U4N server has eight fans with 80 mm diameter. These are arranged as a fan array, consisting of two rows with four fans in each row. The power consumption of such a fan is in the 50 W to 60 W range, for a total of about 400 W to 500 W for the entire fan array.

For the proper cooling of eight 300 W TDP processors in a 2U4N server, this would require fans with 150 W in the same 80 mm diameter form factor. The total fan array will draw about 1,200 W in the case of 300 W TDP processors in a 2U4N server.

The high power consumption of these fans requires thicker current feed lines or higher voltages than the typical 12 V supply can provide. A novel development are fans with 48 V to 54 V voltage specification. These fans can provide four times more power while drawing the same current as fans with a 12 V voltage specification.

The cooling problem gets even more demanding with GPU servers. These servers are popular for applications in Machine Learning and Artificial Intelligence. A powerful GPU server can host from four to eight GPUs in the 300 W to 400 W power consumption range per GPU. For a GPU server with eight GPUs, two processors and ample memory population, the overall power consumption is in the 6 kW range, with about 1.5 kW consumed by internal fans.

Similar to processor development obstacles in recent years, this can be called the "power wall" for fans, where the high power consumption for air cooling is no longer practical.

DLC Concept

Instead of immersing an entire server into the coolant, only the most power-demanding components are cooled, such as:

- Processors
- Voltage Regulator Modules (VRM)
- Accelerators (Vector Processing Cards, GPGPU or GPU)
- DRAM Memory (DIMM) modules
- High-Speed network adapters
- Power Supplies

The list is ordered with increasing complexity and costs, with power supply cooling being the most challenging task.
The typical 2U4N server is the standard for high-density HPC installations. It therefore is the obvious target for a cooling conversion from air-cooling to DLC.

Each of the nodes usually has two processors and 12 to 16 DIMM slots. With the ongoing trend to maximize computing performance per rack unit, there is a demand for processors with ever higher TDP (Thermal Design Power).

DLC to the Rescue

A DLC system consists of the following main components and will be explained in this chapter:

- Cold Plates
- Tubing
- Manifolds
- CDU (Coolant Distribution Unit)

Cold Plates

A first approach for DLC is the use of cold plates on the processors and the VRMs. In a node, the processors and VRMs account for 70 % and upward of the total node power dissipation, so the transition from air-cooling to DLC is greatly lowering the demand for high-performance fans in the chassis. The cold plates of each processor are connected by flexible tubes, thus establishing a cooling loop.

The chilled coolant enters this cooling loop at the inlet side, flows through the front-facing cold plate, the rear-facing cold plate and exits at the hot side of the loop. The coolant is a mixture of water, propylene glycol and biocides. The latter prevent biofilms from forming in the hoses, cold plates and manifolds. This type of coolant is marketed as OAT coolant, which is also used as an antifreeze and anticorrosion coolant for internal combustion engines.

The question whether pure water can be used in a DLC loop is often asked when environmental concerns are an issue. The use of pure water facilitates the growth of biofilms inside the DLC loop and enhances corrosion of wetted components, which in turn lowers the lifetime of the DLC components. Biofilms consist of thermophile bacteria that thrive in a water temperature of 50 °C and higher. This can lead to highly reduced cooling capacity of the cold plates because the biofilms create a thermal insulation layer between the cold plate and the coolant. This is the reason why the use of an OAT coolant is highly recommended. The total amount of coolant in a DLC system is rather small, so it is feasible to use coolant collection systems underneath a DLC-cooled rack and external CDUs at a low price. These systems retain leaked coolant and prevent contamination of the datacenter floor or plenum.

The coolant is forced through the cooling loop by pumps. There are two distinct placements of the pumps:

- Internal pump on each cold plate
- External pump centralized in a rack-mounted or stand-alone CDU (Coolant Distribution Unit)

NEC has considered the second approach in various installations. An external pump system in a CDU leverages “Economies of Scale” effects. In this case, two pumps are used in the secondary loop, for fail-over operations. These pumps are from well-established manufacturers in the HVAC business and are very reliable. In addition, external pumps can be scaled up easily and provide a higher pressure difference and higher coolant flow rate than the highly space-constrained internal pumps, which must fit on the cold plate.

Tubing

The DLC loop has several tubes that make up the full circuit. The internal tubing inside a node is routed through a rear slot panel of the node. The hot- and cold end of the tubing are fitted with couplers that plug into the manifold’s non-spill disconnects. These disconnects prevent coolant from dripping out of the DLC loop in case of a manual disconnect operation, for example for node servicing or replacement. This non-spill disconnects are made of Nickel-plated brass, which is resistant against abrasion and corrosion. The Nickel-plating also enhances surface hardness and allows many connect/disconnect cycles. The valves used in the connectors employ a "flush-face design" to prevent dripping. The construction of these valves also minimizes the volume of air introduced into the coolant loop during every connect/disconnect operation.

The tubing between the manifold and cold plates is made of a material that can sustain the high coolant discharge temperatures for continuous operation, without losing its flexibility or becoming brittle over time.

CDU - Coolant Distribution Unit

The CDU is the heat exchanger that discharges the heat flow from the DLC loop into the primary coolant loop, which is run by the datacenter facility. The CDU is the only active component in the DLC loop if passive cold plates are used. It has several important functions and features:

- Regulation of coolant volumetric flow rate to satisfy a defined temperature spread in the DLC loop
- Discharge of heat into the primary cooling circuit via heat exchanger
- Pump and valve control
- Health monitoring, leakage detection and alerting
- Particle filters for the primary and DLC loop
- Sensors for temperature and flow rate
- Local LCD display and network interface for remote access

A CDU can be either rack-mounted or it can be a row-based type. A rack-mounted CDU has a cooling capacity in the 80 kW to 200 kW range. The lower range of this cooling capacity is sufficient for cooling a fully populated compute rack with high-density 2U4N or GPU servers. The upper range at 200 kW cooling capacity allow one CDU be used for two compute racks. This saves on rack space and can make the tubing more economical.

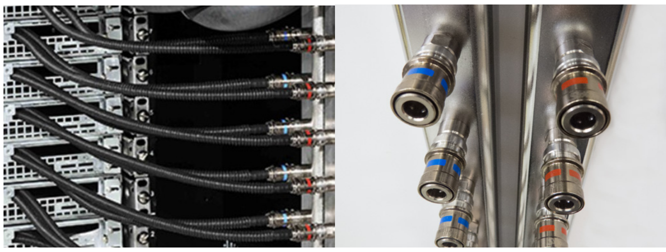
A row-based CDU has a cooling capacity in the 700 kW to 800 kW range. The form factor is in the typical rack standard. Given the high cooling capacity, one CDU can provide cooling for eight to ten compute racks. For large installations with dozens of compute racks, a row-based CDU leverages "Economy of Scale" effects and is generally more cost effective than a number of rack-mounted CDUs with the same cooling capacity as a single row-based CDU.

These CDUs are necessary if the primary coolant loop of the facility is not located in the server room and would be difficult to relocate, or if datacenter guidelines exclude the installation of CDUs inside the server room.

Most CDUs can accept ASHRAE W4 class facility water in the primary coolant loop. (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)). The ASRAE W4 class specifies a maximum water temperature of 45 °C.

Manifolds

The rack manifolds are mounted vertically at the rear of the rack. At least two manifolds are needed. One manifold provides cold coolant inlet, the other accepts the hot coolant outlet.



Since the manifolds occupy additional space in the rear of the rack, a DLC rack is usually deeper than an air-cooled rack. The typical depth of a DLC rack is 1,400 mm.

This leaves enough free space to accommodate the manifolds and power distribution units (PDU) while allowing structured tubing and cabling for power cables and network patch cables.

Example for a 2U4N Server

An example configuration of a 2U4N diskless server for HPC applications can look as follows:

- 2U chassis with dual power supplies
- 8x processors with a TDP (Thermal Design Power) of about 200 W
- 64x 32GB DDR4 ECC registered DIMMs
- 4x InfiniBand HDR HCA

The AC power consumption of this server, when fully air-cooled, is about 2,850 W, if operated with full processor and memory load. The same configuration with a processor and VRM cooling loop has a power consumption of about 2,500 W. This lower power consumption of the DLC version compared to the air-cooled version is due to lower fan speeds. The internal fans only need to provide cooling air for the DIMM modules HCA and some motherboard components, like baseboard management controller and onboard network chips. It is important to note that the power supplies of a 2U4N server will typically be air cooled, even in a DLC system. While DLC-cooled power supplies are available, the added price for tubing and connectors often does not make this an economical option.

The DLC version in this example discharges 55 % of the total heat flow of 2,500 W into the coolant.

There are several assumptions underlying this calculation. The first concerns the server intake temperature. In most DLC scenarios, this temperature is in the 30 °C to 40 °C range. The second value is the temperature spread ΔT of the coolant in the cooling loop. This is defined as the temperature difference in K (Kelvin) from the outlet (hot) side over the inlet (cold) side.

A typical value for this spread over one processor is in the range of 3 to 5 K, so up to 10 K per cooling loop.

Improving DLC Efficiency

The 55 % water-to-air ratio can be improved by extending the cooling loop over the DIMMs and the HCA. This adds complexity to the cooling loop. The DIMM slots in a 2U4N server are very tightly spaced. This "narrow pitch" design is necessary to accommodate enough DIMM slots on a mainboard, but it requires a special design of the cooling element for the DIMMs, so they can fit into the space between two modules.

The cold plate on the InfiniBand HCA must be designed so the card can be replaced easily in case of failure. This can double the price of such an extended cooling loop compared to the CPU and VRM cooling loop version.

In the example of the 2U4N diskless server, the efficiency is improved to 70 % of the total heat flow discharged into the coolant. The power consumption remains practically the same as in the CPU and VRM cooling loop version, as the fan speed is reduced only slightly more.

High End DLC

Improving the figure of 70 % water-to-air ratio is a difficult task, as it implies that the power supply be included in the DLC system. Power supplies have complex interiors which differ from the predominantly planar arrangement of components on a mainboard, GPU or HFA. This leads to intricate routings of the cold loop, to make sure that enough heat flow is transferred into the coolant.

The overall contribution of the power supply compared to the heat discharged into the DLC system of a typical 2U4N server is in the range of 10 %. If the mechanical overhead for DLC cooling of a power supply is compared to the gain in DLC efficiency, this leads to diminishing returns.

Depending on the implementation, this can push the coolant-to-air ratio to 80 %. Due to the heat emitted from the cold plates, there must be a certain airflow to remove the 20 % of heat flow into air within the racks.

This is accomplished by using in-row coolers or rear-door coolers that absorb this heat flow and transfer it to cold facility water. Since the racks are completely closed, there is no heated air escaping into the datacenter. The only heat source are the rack surfaces, but this can be minimized by using a foam insulation on the interior of rack walls, roof and doors. Such a combination of DLC and ILC (Indirect Liquid Cooling) provides a balanced cooling solution with an optimized TCO.

Accelerator Cooling

The typical accelerators in an HPC environment are GPGPUs, often just abbreviated as GPUs or special compute-accelerators like the NEC SX-Aurora TSUBASA vector card. The power requirement of these devices is at the 300 W to 400 W level.

A specialized server can house up to eight of these accelerators, thus creating the demand to remove up to 4 kW of heat flow. This creates a formidable challenge for an air-cooled system, so a DLC cooling loop for the GPUs is an important step to reduce the power of the fans. The water-to-air ratio can reach 80 % for such a server.

Pushing up the Heat

There is a demand for increasingly higher temperatures at the inlet of the cooling loop. This is mainly driven by the desire to reuse the discharged heat for heating buildings near the datacenter. For this application, the inlet temperatures are often pushed to 50 °C, with a ΔT of 10 K, for an outlet temperature of 60 °C.

The high outlet temperature pushes the last cooled device in a cooling loop to its thermal limits. The Arrhenius law for electronics states that a temperature increase by 10 °C reduces the useful lifetime of a circuit by 50 %. This should be regarded as a rule of thumb only, but it shows how higher temperatures in the cooling loop are detrimental to the lifetime and reliability of the equipment. The maximum outlet temperature will thus be determined by providing a large enough margin for the lifetime of the electronics, to ensure reliable operation during the lifecycle.

While the prospect of using the discharged heat for heating buildings seems valuable for reducing the CO2 footprint of a campus, it should be seen that this could fall under the law of diminishing returns by compromising the stability and longevity of the HPC systems.

The ASHRAE W4 class allows facility water-supply temperatures of 2 °C to 45 °C. The W5 class raises this value to >45 °C, without giving an upper limit. This class was added to allow building heating systems. Primary coolant loop outlet temperatures of 50 °C will generally already allow dry air cooling in a cooling tower in most regions.

It should be noted that in most cases, chillers will still be required to provide a certain amount of cold water for the cluster. This is necessary to cool IT equipment that does not have a DLC system, like power supplies of compute servers, network switches and storage devices that house hard disks.

TCO Example

The TCO is an important metric for a cluster system. It can yield insight into the benefits of a DLC solution. For this example, three cooling versions for the compute nodes are used:

- ILC, with in-row coolers
- DLC, processor cooling only
- DLC, processor, memory and InfiniBand cooling

The cluster in the example consists of 100 2U4N servers, for a total of 400 compute nodes.

Compute server details:

- 2U quad-node chassis, dual 2,200 W power supplies
- 8x processors (AMD Epyc 7002 series or Intel Xeon "Cascade Lake Refresh", 225 W TDP
- 64x 32GB DDR4-3200 memory modules, ECC
- 4x InfiniBand HDR100/EDR HCA
- 4x NVMe SSD, 1.6 TB, for local scratch memory

The example also includes a storage system for a parallel file system, consisting of three JBODs as OST (Object Storage Target), one MDT (Metadata Target) system with NVMe drives for fast metadata storage, two OSS (Object Storage Server) and two MDS (Metadata Storage Servers). The raw storage capacity is 2.5 PB. All storage components are ILC-cooled.

The high-speed network is an InfiniBand HDR/HDR100 network. There are six core-layer switches and twelve edge-layer switches. The connection speed between core and edge switches is 200 Gbit/s, the compute nodes are connected with HDR100 speed, at 100 Gbit/s. The administration- and service network is designed with 1 Gbit/s Ethernet components. All network components are ILC-cooled.

The infrastructure of the cluster consists of racks with in-row coolers and a CDU in case of the DLC solutions. The administration nodes are also part of the infrastructure. They consist of five 1U rack servers with a single processor only. The important services for cluster operation are implemented as Linux containers on these administration nodes. These services include the user login, scheduler, Node-Image deployment and others. The administration nodes are ILC-cooled because they have a low power consumption and would not justify the expense of a DLC system.

For the calculation of the total power consumption, it is assumed that all processors are driven to their full TDP value and memory modules are also under full load. The following table shows the power consumption of the three cooling solutions.

As expected, the DLC versions B and C have a lower total power consumption compared to the ILC-cooled version A. The main contribution to the power savings is the lower fan speed

	Version A ILC	Version B DLC, processor only	Version C DLC, processor, memory and InfiniBand
100x 2U4N	309.94 kW	273.47 kW	269.05 kW
Storage	6.65 kW	6.65 kW	6.65 kW
Network	15.76 kW	15.76 kW	15.76 kW
Infrastructure	19.83 kW	13.23 kW	10.23 kW
Power Consumption Cluster	352.18 kW	309.11 kW	301.69 kW

of the 2U4N servers. A secondary contribution comes from the lower number of in-row coolers that is required for the DLC versions. The ILC-cooled version uses six in-row coolers, in comparison to three for version B and only two for version C.

It can also be seen that the power consumption of the compute nodes in version C is only marginally lower than version B. This is an example of diminishing returns.

The TCO calculation is based on assumptions for the PUE (Power Usage Effectiveness) of a datacenter. There are three typical PUE values:

- PUEair for air-cooling: 1.35
- PUEcold for cold water, used for ILC: 1.2
- PUEwarm for warm water, used for DLC: 1.05

These values reflect the overhead in cooling infrastructure in the datacenter. The exact values depend on a number of different factors. The location of the datacenter is one such factor. A low average temperature over the year can lower the PUE values, since less energy is necessary to provide datacenter cooling.

The PUEair is the highest value, as air cooling of servers requires the biggest overhead with active chillers and fans. The typical air temperature provided for server cooling is in the range of 20 °C to 25 °C. The high PUE is the key argument against an air-cooled cluster system and it is not considered in this comparison.

The ILC version requires active chillers too but can save on fans, which leads to a lower PUE value PUEcold, compared to PUEair. The cold water of the facility is delivered to the in-row coolers at a temperature in the range of 15 °C to 25 °C, for the ILC system. This is the preferred cooling for storage- and infrastructure components.

DLC can accept warm water in the range of 35 °C up to 50 °C, depending on the implementation of the cold loop in a server. The datacenter can use free cooling in its chillers most of the time, so the heat pumps of the chillers only need to operate on hot days, leading to the low value for PUEwarm.

The storage, network and infrastructure components of the cluster are ILC cooled, so they require cold water, while the 2U4N compute servers are DLC cooled, with warm water. The datacenter power consumption in the following table is calculated by using the respective PUE values for ILC and DLC.

The energy cost is assumed with 0.22 €/kWh. Depending on the size of the datacenter and geographic location, this can vary significantly.

	Version A ILC	Version B DLC, processor only	Version C DLC, processor, memory and InfiniBand
Power Consumption Cluster	352.18 kW	309.11 kW	301.69 kW
Cluster Cost	7,012,000 €	7,132,000 €	7,318,000 €
Datacenter Power Consumption	422.61 kW	344.33 kW	329.45 kW
Energy Cost over 5 Years	4,072,000 €	3,318,000 €	3,175,000 €
Energy Cost over 7 Years	5,701,000 €	4,645,000 €	4,445,000 €
TCO over 5 Years	11,084,000 €	10,450,000 €	10,493,000 €
TCO over 7 Years	12,713,000 €	11,777,000 €	11,763,000 €

Based on these values, the TCO is calculated as the sum of the cluster cost and the energy cost over a reasonable useful operational life of the cluster.

The table shows significant cost savings of version B compared to version A of about 630 k€ over five years of cluster operations and about 930 k€ over seven years.

Version C shows a slightly higher TCO over five years than version B, due to the higher initial cost of the cluster and relatively low additional power reduction. The TCO value for seven years justifies the higher hardware cost marginally.

These examples show the merit of a DLC solution with a processor-only cold loop, as in version B. The more complex cold loop of version B is still a viable option, if the compute nodes have a high memory population, for example with 128 GB modules and fully populated DIMM sockets. This justifies the memory cold loop. An InfiniBand HCA with full HDR speed consumes about 30 W of power, compared to the HDR100 HCA used for the example. All these factors contribute to the lower power consumption of version C over version B and can lead to a lower TCO even over a five-year period.

DLC vs. Immersion Cooling

The market for Immersion Cooling (IC) is smaller than that for DLC but seems to gain interest in HPC and in the OCP ecosystem.

There are some aspects that need to be considered when comparing IC with DLC. Older systems used oil as a coolant. NEC has a testbed configuration called TSUBAME-KFC, which employs a non-toxic low viscosity oil as a coolant. The submersion rack is the key element in the system. It resembles a 19" rack laid on its side.

All compute nodes are completely immersed in the coolant. The fans in the power supply were removed, so the coolant can flow through them freely. The passive heat sinks on the processors use thermal grease for air- or DLC versions. This grease had to be replaced with thin metallic sheets, since the oil will dissolve the grease.

No other modifications to the compute nodes were necessary. Oil-based LC solutions require a careful choice of the oil. The flashpoint must be high enough to limit the fire hazard that the oil poses. In the TSUBAME-KFC, an oil is used with a flashpoint of 260 °C. Another requirement is low viscosity, so the oil can achieve a high flowrate around thermally demanding components and thus provide a high heat transfer.

Another choice for an LC coolant is a dielectric fluid. The low specific heat capacity of these coolants require that the coolant undergoes a phase change around heatsinks, which need a high heat transfer. This phase change from the liquid phase into the gas phase is a hallmark of dielectric fluid cooling.

Advantages

- Servers can be immersed entirely in the coolant bath, including the power supplies, without fans.
- Sealed hard disks, filled with Helium, can be used.
- Potentially higher server density than DLC, but the higher floor-loading due to the large amount of coolant required must be taken into consideration.

Disadvantages

- Facility cold water in the primary coolant loop is required for dielectric fluids, to condense coolant vapor back to the liquid phase.
- Dielectric fluids contain perfluorotributylamine and perfluorohexane. The extremely high global warming potential of 7,000 times that of CO_2 over a 100-year interval makes these problematic compounds, as there is inevitable leakage into the atmosphere.
- Due to the high chemical stability of the carbon-fluorine bond, the molecules of dielectric fluids persist in the atmosphere for centuries.
- The low surface tension of dielectric fluids can lead to fluid intrusion into power- and data cables.
- Servers and other immersed equipment are often exposed with their components to the liquid, without metal covers, to optimize cooling. This poses a damage risk during servicing.
- Servicing time is higher than for DLC - or ILC solutions. In case of oil-based ILC solutions, the components removed from the coolant bath must be thoroughly cleaned, to remove any residual oil.
- Oil-based coolants tend to creep and can contaminate the datacenter, if not carefully sealed inside the submersion racks.

DLR CARA Cluster

The DLR (German Aerospace Center, "Deutsches Zentrum für Luft- und Raumfahrt") operates the CARA cluster since February 2020. The machine is used for aerospace simulations, culminating in the concept of a "virtual aircraft", which combines the design and complete simulation workflow in a digital model.

Key features:

- 570 2U4N servers, for 2,280 dual processor nodes
- 4,560 AMD Epyc 7601 32-core processors
- 145,920 cores total
- DLC processor-only cooling loop
- 30 DLC cooled racks with 15 in-row coolers
- InfiniBand HDR core switches, HDR100 edge switches
- Two ILC-cooled racks with in-row cooler, for storage system, service nodes and network infrastructure

CHMI Cluster

The Czech Hydrometeorological Institute (CHMI) put an NEC SX-Aurora TSUBASA supercomputer into service. The newly deployed HPC solution is used for high-resolution regional climate modelling. NEC has realized a highly efficient DLC concept with cold water by combining leading-edge DLC and side cooler technology to avoid any leakage of waste heat into the computer room, which allows the complete system and the environment to operate without any additional air-conditioning in place:

Key features:

- Direct DLC without CDU
- Coldwater cooling
- 48 NEC SX-Aurora TSUBASA Servers
- 384 Vector Engine PCIe Cards
- 4 Racks
- 3 In-row coolers (2+1 Redundant)
- 2 PB Storage

DWD Cluster

The DWD (Deutscher Wetterdienst) provides numerous meteorological and climatological services. This includes short- and medium-term weather forecasts, meteorological information for aviation and maritime safety and long-term climate modeling.

The DWD cluster utilizes the NEC SX-Aurora TSUBASA vector engine. Eight vector engines are installed in an NEC A412-8 Server vector host system.

Key features:

- 104 NEC A412-8 servers with single AMD Epyc processor and eight SX-Aurora TSUBASA vector engines
- DLC cooling loop for SX-Aurora TSUBASA, with cooling for the processor die and HBM2 memory chips
- 12 DLC cooled racks with 15 in-row coolers
- InfiniBand HDR core switches, HDR100 edge switches

Glossary of Terms

ΔT .... Temperature difference, often used as temperature spread, measured in K
ASHRAE .... American Society of Heating, Refrigerating and Air-Conditioning Engineers
CDU .... Coolant Distribution Unit
DLC .... Direct (Chip) Liquid Cooling
ECL .... Emitter Coupled Logic
GPU .... Graphics Processing Unit
HCA .... Host Channel Adapter
HVAC .... Heat, Vacuum and Air Conditioning
IC .... Immersion Cooling
ILC .... Indirect Liquid Cooling
Kelvin .... Kelvin temperature scale; 0 K = -273.15 °C
PUE .... Power Usage Effectiveness
TDP .... Thermal Design Power
VRM .... Voltage Regulation Module

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