White paper

Hydraulic design principles for efficient direct liquid cooling infrastructure

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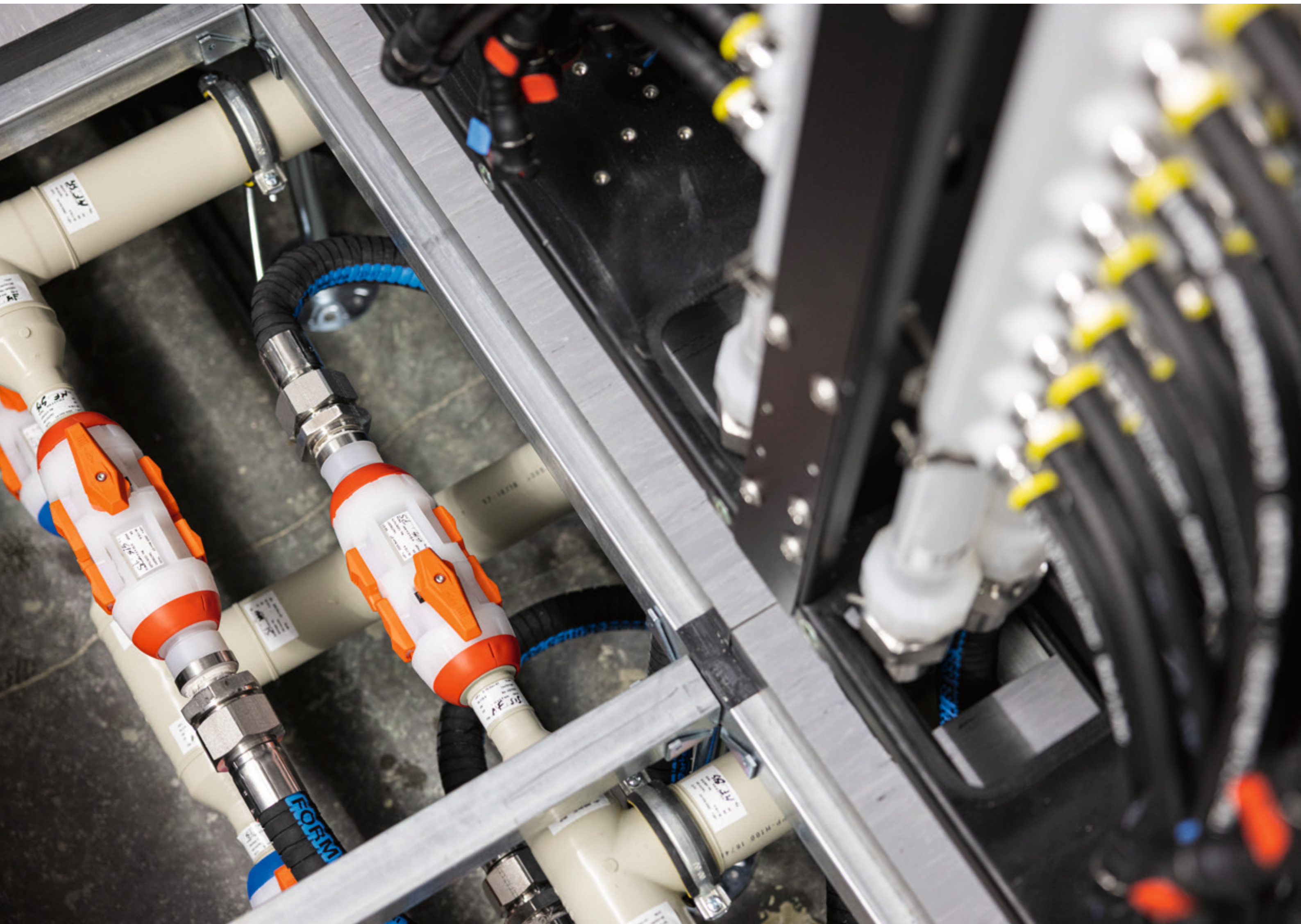

Abstract

As direct liquid cooling becomes essential for high-density Artificial Intelligence (AI) and high-performance computing (HPC) deployments, the hydraulic architecture and flow design of the cooling loop have become critical determinants of both energy efficiency and long-term operational reliability. Yet hydraulic performance, coolant conveyance, and flow behavior are often underappreciated in data center design, particularly by stakeholders with limited hydraulic expertise.

This paper examines how hydraulic design and engineered piping systems influence pressure loss, hydraulic balancing, erosion risk, and overall system performance in direct liquid cooling applications. Using flow calculations and computational fluid dynamics (CFD) based on Schneider Electric's EcoStruxure Reference Design 109, the analysis compares polymer and stainless steel configurations at the system and rack levels and evaluates the effects of manifolds, valves, couplings, and balancing.

The results show that hydraulic performance is governed by overall design quality rather than material alone, while also demonstrating that polymer solutions can provide lower pressure loss in critical assemblies, reduced weight, and advantages in corrosion resistance, reduced fouling potential, improved wetted-material compatibility, and long-term coolant stability.

The analysis further highlights that local flow conditions, including local velocities and flow restrictions, influence not only pumping energy requirements but also operational reliability.

The paper concludes that efficient and reliable cooling systems require careful hydraulic engineering by experienced specialists, and that appropriately designed polymer piping systems are a technically sound option for modern data center applications.

This publication is part of GF's ongoing technical series on direct-to-chip liquid cooling, developed to provide engineers, consultants, OEMs, and data center operators with practical guidance on the design of reliable and energy-efficient cooling infrastructure. While the previous paper introduced the role of engineered polymer piping systems in direct liquid cooling, this paper focuses specifically on hydraulic design principles that govern pressure loss, flow distribution, and overall system performance.

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Abbreviations

AI	Artificial Intelligence
CDU	Coolant distribution unit
CFD	Computational fluid dynamics
DECS	Datacom equipment cooling system
DLC	Direct liquid cooling
HPC	High-performance computing
OCP	Open Compute Project
PUE	Power usage effectiveness
RoHS	Restriction of Hazardous Substances
SCH	Schedule
SDR	Standard dimension ratio
TCS	Technology cooling system
UQD	Universal Quick Disconnect

Unit convention

Unless otherwise stated, SI (metric) units are used throughout this paper. Product sizes follow their respective industry standards. Polymer piping is designated using metric dimensions (d/DN and SDR), while stainless steel piping and selected commercially standardized components (e.g., manifolds, hoses, and couplings) are designated using nominal inch sizes and Schedule (SCH) classifications where appropriate.

1. Pressure loss as a measure of cooling system energy overhead

Accelerating digitalization will have an enormous impact on data centers over the coming years. As computing power density skyrockets across AI training clusters, machine learning inference platforms, and large-scale HPC deployments, the need for capable cooling deployments grows correspondingly. At present, the most prominent liquid cooling technology is single-phase (water or propylene glycol-based) direct liquid cooling (DLC).[1] Direct liquid cooling removes heat at the source by transferring thermal energy from high-power electronic components, such as CPUs and GPUs, to a liquid coolant through specially designed cold plates.

The coolant circulates through a closed-loop piping network and hydraulic conveyance system connecting the cold plates with a coolant distribution unit (CDU). The CDU regulates key parameters, like coolant temperature, volumetric flow rate, and system pressure, ensuring that chip temperatures remain within specified limits and that the required pressure cascade is maintained across the cooling loop. As a result, CDU power consumption is the energy required to operate the cooling system and therefore makes hydraulic efficiency a key lever for cooling system energy overhead and pumping energy demand.

As data centers face growing energy-efficiency and sustainability demands, they are increasingly optimized for power usage effectiveness (PUE). PUE is defined as the ratio of the total power consumption of the data center to the power consumption of the IT equipment. A perfectly efficient data center, therefore, has a PUE of 1.[2] For years, the industry average has been around 1.5[3], yet the latest top performers achieve a PUE of 1.09[4].

In the pursuit of minimizing PUE, the parasitic load associated with coolant circulation plays a vital role, as any power used for coolant distribution directly increases total facility energy without contributing to IT load. The key design parameter in any liquid cooling loop is pressure loss, also called pressure drop (Δp), that occurs when the coolant flows through pipes, fittings, valves, cold plates, heat exchangers, and other hydraulic components. Pressure loss directly represents the amount of hydraulic energy lost due to friction and flow restrictions, as higher pumping power is required to maintain the target flow rate. Excessive pressure drop, therefore, not only raises energy consumption but also increases the mechanical load on pumps and other system components, which may adversely affect their service life.

While cold plates remain the dominant hydraulic contributor in direct liquid cooling systems, infrastructure design determines how much additional pressure drop and pumping energy are introduced throughout the remainder of the cooling loop.

Furthermore, if the cooling loop is not adequately sized, the CDUs may be unable to deliver the required coolant flow under high operating conditions. In such cases, excess heat must be removed by conventional air-cooling systems, which significantly reduces the overall efficiency of the data center.

1 Kulkarni et al., 2025
2 Avelar et al., 2012
3 Davis, 2024
4 Crosley, 2026

2. System level hydraulic optimization: Design approach

Schneider Electric's EcoStruxure Reference Design 109[5], recognized as the first build-ready reference design specifically developed for next-generation AI data centers, is used as the basis to investigate hydraulic efficiency in DLC piping design in detail. This reference framework was developed to support liquid-cooled racks up to a rack density of 132 kW, with liquid-to-liquid CDUs and fluid coolers with adiabatic assist.

The flow analysis is performed in this design with both stainless steel and polymer piping systems using the Sinetz software from Sigma Ingenieurgesellschaft mbH and ANSYS CFD software. Key design parameters and the component selection of each system are summarized in Table 1.

For the hydraulic analysis, one of the three clusters defined in the reference design was considered. The cluster comprises 16 racks, each supporting a maximum power density of 132 kW, corresponding to a total rack load of approximately 2.1 MW. Two liquid-to-liquid CDUs serve the cluster, with each CDU supplying eight racks.

Assuming a temperature difference of 10°C (18°F) between the rack inlet and outlet, the eight-rack section served by each CDU requires a total volumetric flow rate of approximately 23 L/s (6.07 US gal/s). This calculation is based on the typical thermophysical properties of a 25% propylene glycol solution (PG25) at 40°C (104°F).

The inlet pressure was specified at 4 bar (58.01 psi) and the pipe dimensions were determined by using the steel configuration as a baseline and matching the polymer inner diameter to the steel.

The resulting pressure loss of the system, calculated as the difference between the inlet and outlet pressures, was 1.98 bar (28.72 psi) for the polymer configuration and 2.31 bar (33.50 psi) for the steel configuration. Figure 1 depicts the pressure loss of the polymer configuration.

5 Schneider Electric, 2021
6 Chen et al., 2023

Table 1: Component list of the researched flow simulation based on Schneider Electric's EcoStruxure Reference Design 109.

ID	Component	Count/Length	Polymer	Stainless Steel
1	**Shut-off valve**	22	GF 546 Pro / 565 DN150	Butterfly TYP 038
2	**Supply and return pipeline**	70 m (229.66 ft)	PROGEF PP-H d160/SDR11	SCH10 stainless / EN 10357 / 3A / ASME BPE 5"
3	**Hose big**	32	Parker E-Z FORM™ 2" cooling hose	Parker E-Z FORM™ 2" cooling hose
4	**Large quick disconnector valve**	32	LiquidCore QC7 2" modeled as 2 x PP Ball valves	Danfoss Hansen FD 83 2"
5	**Manifold**	32 à 1.8 m (5.90 ft) with 24 outlets	LiquidCore d63 PVDF	Square profile 1,5"
6	**Small quick disconnector valve**	32 x 24 x 2	Danfoss Hansen Universal Quick Disconnect (UQD04)	Danfoss Hansen Universal Quick Disconnect (UQD04)
7	**Hose small**	32 x 24	Datacenter Cooling hose 3/8" inner diameter = 9.5 mm	Datacenter Cooling hose 3/8" inner diameter = 9.5 mm
8	**Cold plate**	16 x 24	1.2 bar (17.40 psi) pressure[6] drop for all cold plates and internal piping	1.2 bar (17.40 psi) pressure[6] drop for all cold plates and internal piping
9	**Control valve**	16	Not included in the pressure-loss calculation; discussed separately in Chapter 7.	Not included in the pressure-loss calculation; discussed separately in Chapter 7.

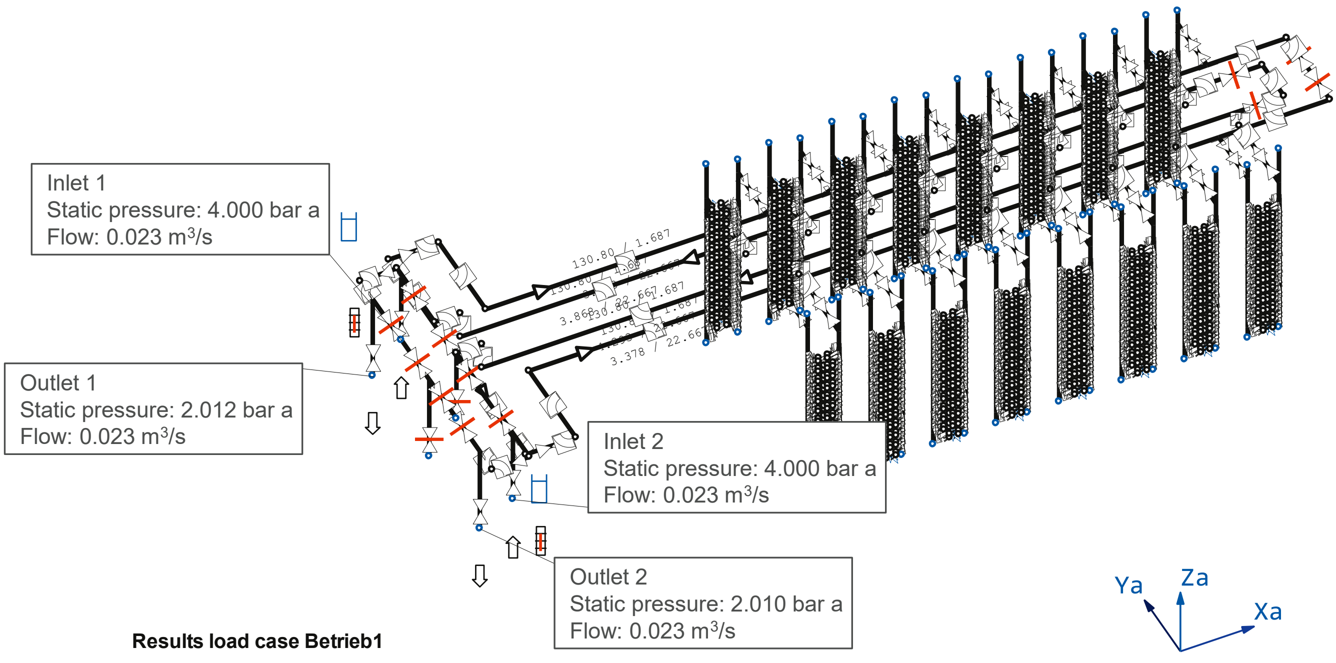


Figure 1: Pressure loss in Schneider Electric's EcoStruxure Reference Design 109 modeled with polymer components.

When evaluating polymer and steel piping systems, it is important to consider that the systems differ in several key design parameters, such as pipe diameter, wall thickness, and joining technology. For thermoplastic pipes, the standard dimension ratio (SDR) is commonly used to classify pipe dimensions. This measure defines the ratio of a pipe's outside diameter to its wall thickness as a universal way to classify the pressure rating for polymer piping.

For steels, schedule (SCH) is a standardized system used to define pipe wall thickness. The schedule number, e.g., SCH 10, SCH 40, or SCH 80, indicates a specific wall-thickness category within the ANSI system[7]. As such, the different standards are not one-on-one comparable, but a skilled designer can select an alternative based on the system requirements.

Pressure resistance in both thermoplastic and metallic piping systems is determined by the combination of material properties and pipe geometry, particularly the relationship between diameter and wall thickness.

7 Kadezabek, 2025

3. Auxiliary components drive the pressure loss of a DLC system

Pressure loss in the different system components is analyzed in Figure 2. Cold plates dominate overall pressure drop in direct liquid-cooling systems, although avoidable infrastructure losses are also an important contributor to pumping energy and operational margins. This is widely acknowledged, as modern cold plates are designed with microchannels or jet-impingement structures to achieve high heat transfer coefficients at the chip interface[8]. These structures impose narrow hydraulic diameters and complex flow redirection patterns. As a result, the fluid experiences significant viscous shear and form losses, resulting in a higher pressure drop than the rest of the circuit.[9] Here, cold plate geometry was not modeled, but the effect was included with a rather conservative pressure loss of 1.2 bar (17.40 psi)[10] over all servers. As indicated in Figure 2, this pressure loss represents more than half of the total loss in the entire circuit.

As contaminants or particles can easily block the tiny micro-features, interfering with the flow, maintaining the fluid purity is of critical importance for both preserving cooling performance and optimizing energy performance[11]. Consequently, the piping design should avoid dead ends or oversized sections that could create areas of low velocity or standing water. These conditions increase the risk of corrosion, fouling, and biofilm formation, ultimately leading to accelerated coolant degradation. Here, polymer configurations can provide fundamental benefits as they are inherently corrosion resistant and minimize biofilm growth with smooth inner surfaces[12].

8 Xiao et al., 2022
9 Zhang et al., 2024
10 Gite, 2026
11 Torres Arango et al., 2025
12 Hyde et al., 1997

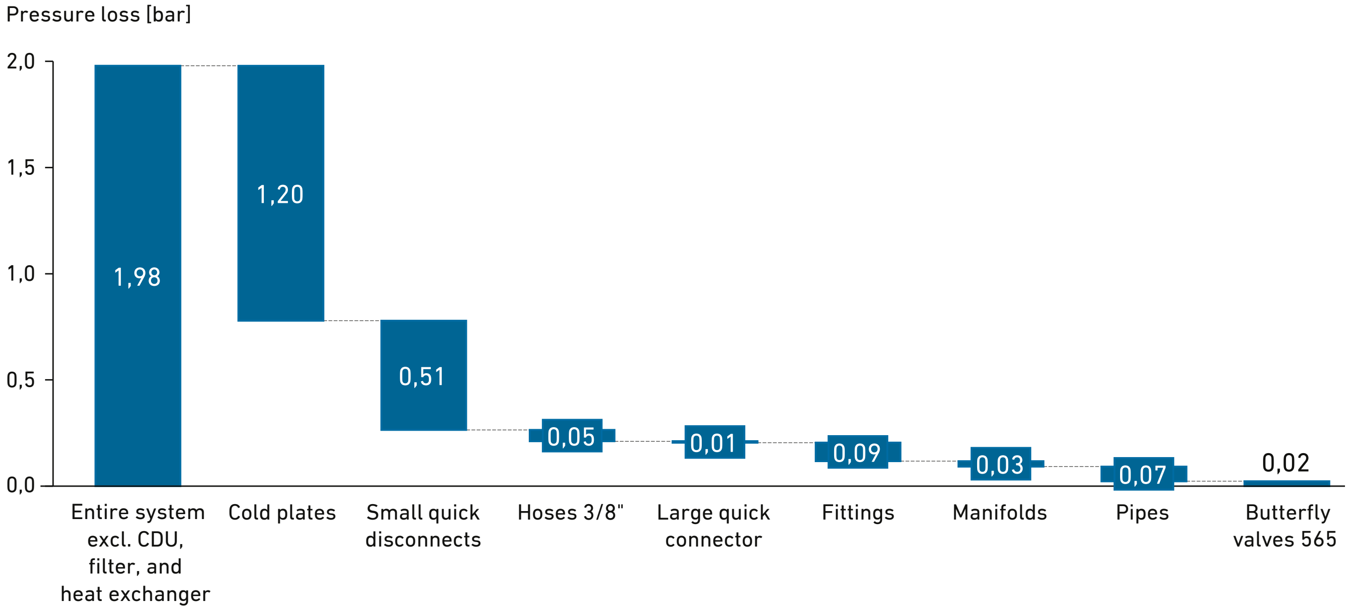


Figure 2: Pressure loss distribution of Schneider Electric's EcoStruxure reference design 109 modeled with polymer components.

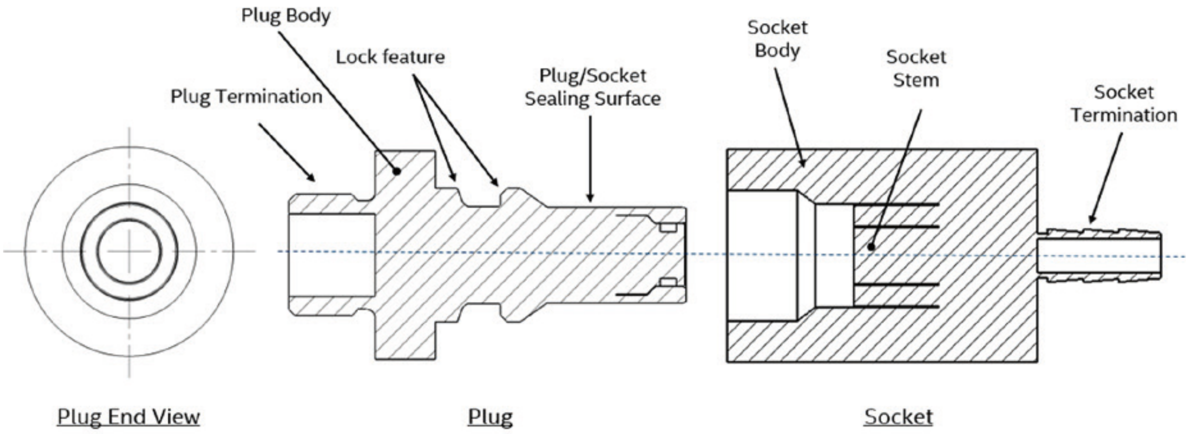


Figure 3: Anatomy of a UQD[13]

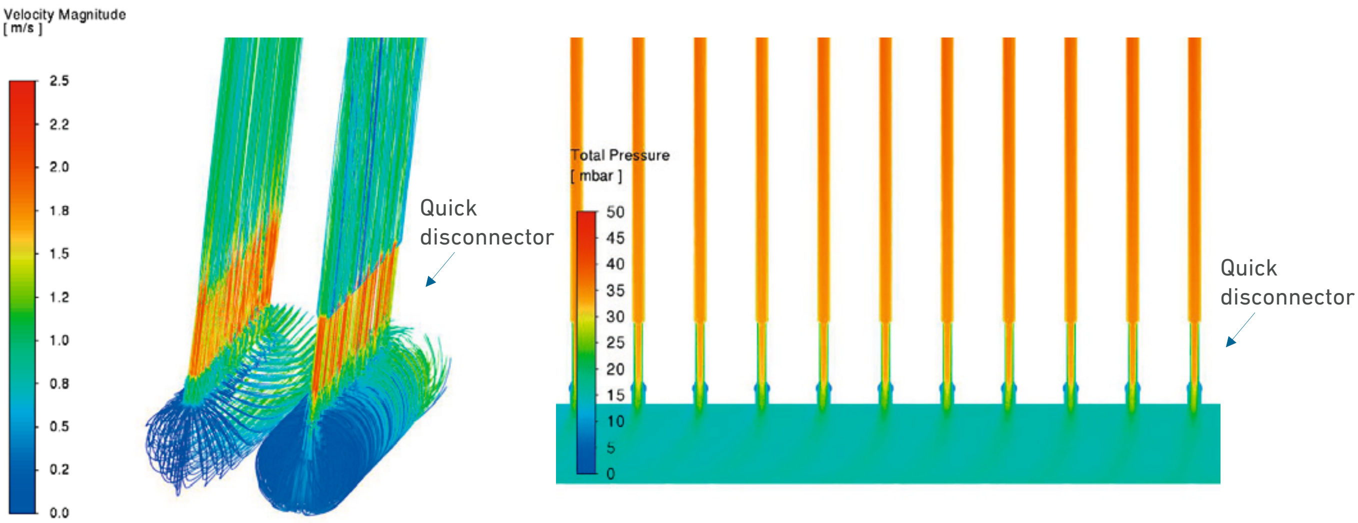


Figure 4: Impact of quick disconnectors on flow velocity and total pressure. Connectors sit at the indicated location.

Major pressure loss occurs as well in the couplings, also called small quick disconnects or UQDs, if couplings adhering to standards from the Open Compute Project (OCP) are used.[13] These couplings are available in a variety of styles, but the general anatomy is relatively common. The couplings consist of two halves, which are often gendered male/female, or more technically called plug/socket or insert/body (Figure 3). Due to their relatively small internal flow passages, a local flow constriction is introduced that increases fluid velocity and turbulence, leading to a significant pressure drop across the connection. The impact is visualized in a CFD simulation following Schneider Electric's EcoStruxure Reference Design 109 in Figure 4. Together, cold plates and couplings account for over 85% of the entire pressure loss in the presented case.

In DLC systems like the one described in Chapter 2, these couplings are employed at the server level to connect and disconnect IT equipment during operation.[14] They must not be confused with larger-diameter, high-flow couplings, also called double-isolation valves or large quick connectors, which are employed in branch line assemblies to separate entire racks from the cooling system. While these share the same functional connect-disconnect principles, they usually feature a symmetric design. Large quick connectors are examined in Chapter 5.

13 Sprenger, 2020
14 ASHRAE Technical Committee 9.9, 2019

4. Manifold geometry as a lever for hydraulic performance

A manifold is a flow component used to distribute or collect fluid from multiple parallel branches in a hydraulic system. It typically consists of a main header with several outlets (or inlets), allowing one supply line to feed multiple consumers. In DLC applications, manifolds split the rack coolant supply into parallel streams for each individual server and then collect the return flow back into a single outlet (Figure 5). To minimize the impact of the manifolds on the overall system performance, the manifolds must be dimensioned appropriately to support the full rack-level cooling load.

As illustrated in Figure 6, the simulation of Schneider Electric's EcoStruxure Reference Design 109 indicates a rack-level pressure loss difference of 0.37 bar (5.37 psi) between the steel and polymer configurations. The steel configuration has approximately 19% higher total system pressure loss than the polymer configuration, closely matching the observed system-level difference. The observed reduction originates primarily from hydraulic geometry, local pressure recovery, and flow guidance rather than material selection alone.

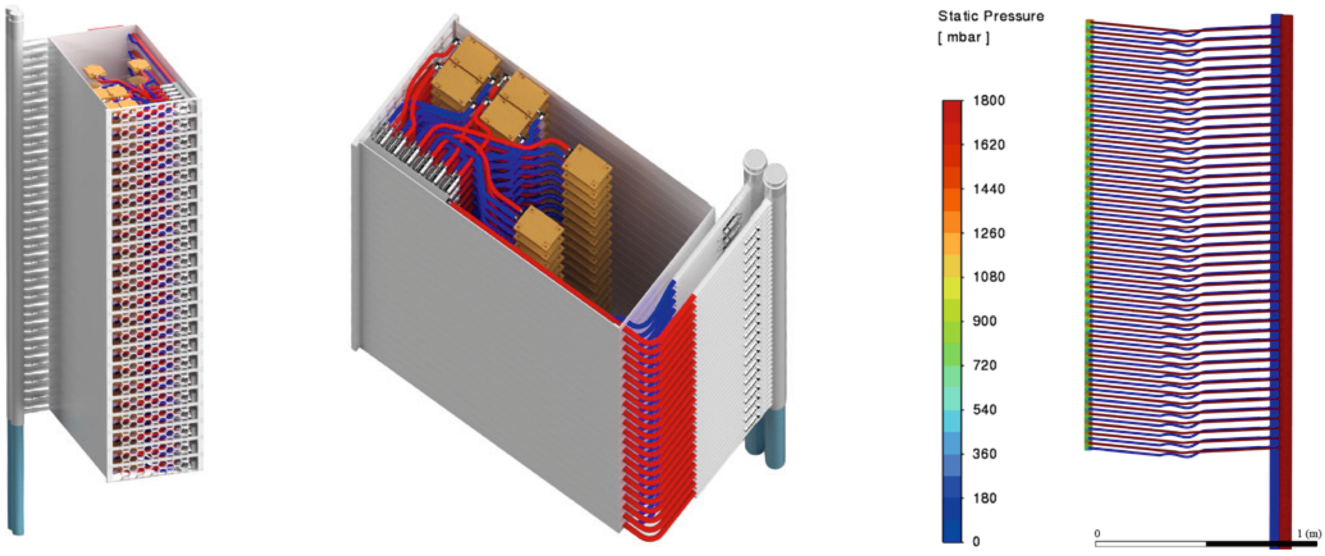


Figure 5: Simulation of manifolds in a rack assembly. Circular d63 manifolds with 44 branches are used. The volume flow is defined as 170 l/min.
Cold plates are modeled as porous domains with a predefined resistance.

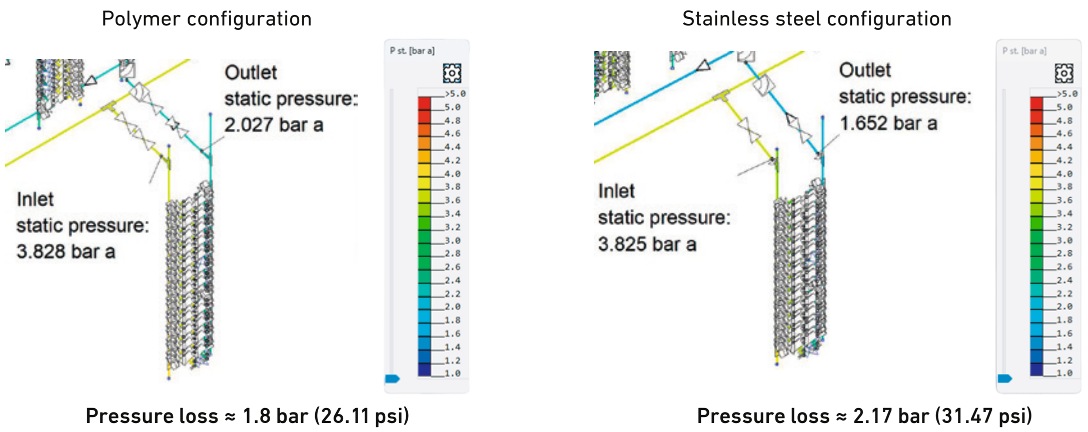


Figure 6: Rack-level pressure loss difference of 0.37 bar (5.37 psi) (19%) between the steel and polymer system.

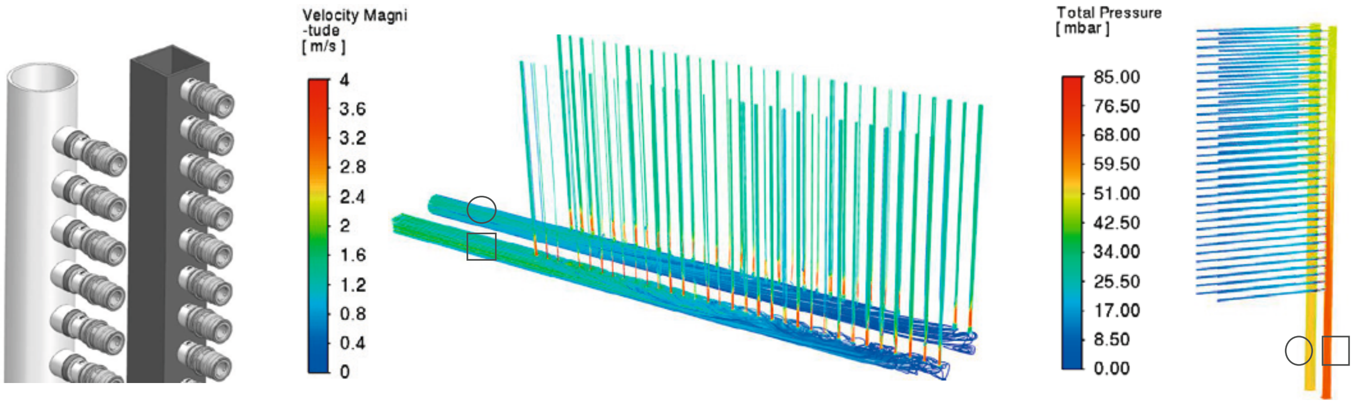


Figure 7: Side-by-side comparison of the flow behavior in round and rectangular manifolds. The round manifold reduces pressure drop by approximately 20% at the same volumetric flow rate.

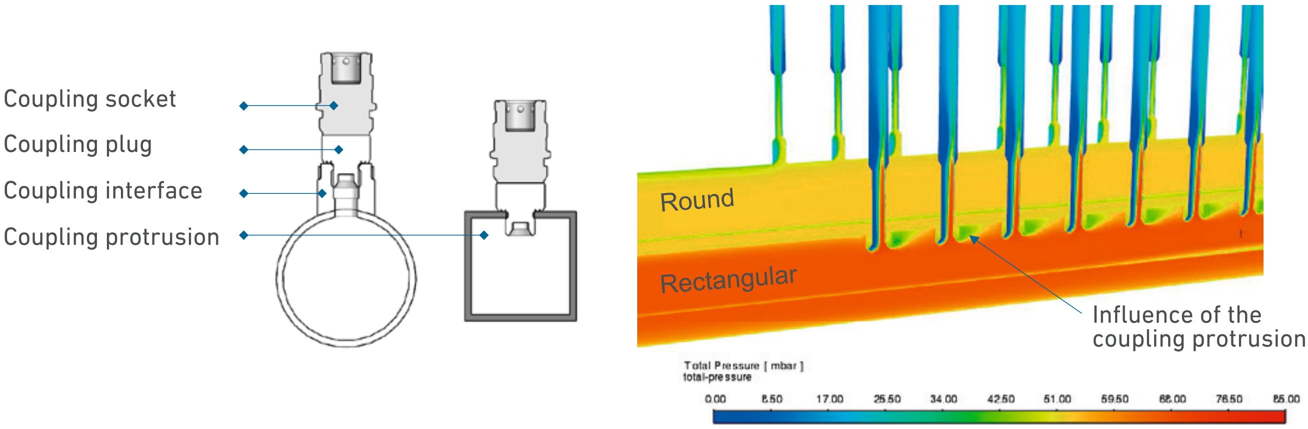


Figure 8: Manifold schematics (left) and the impact of coupling protrusion on pressure distribution (right).

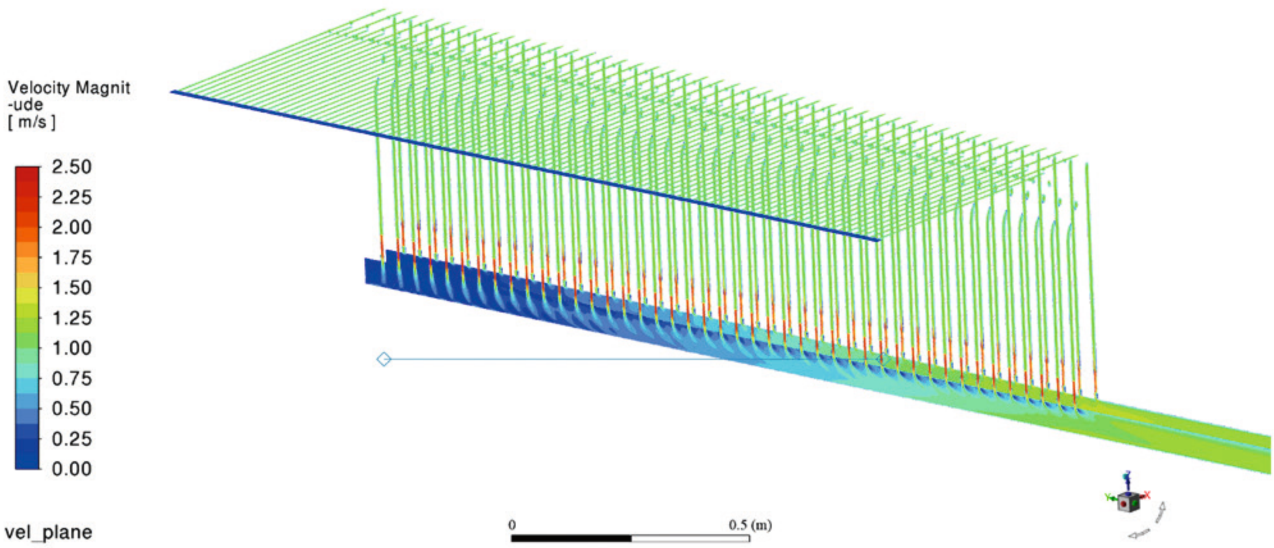
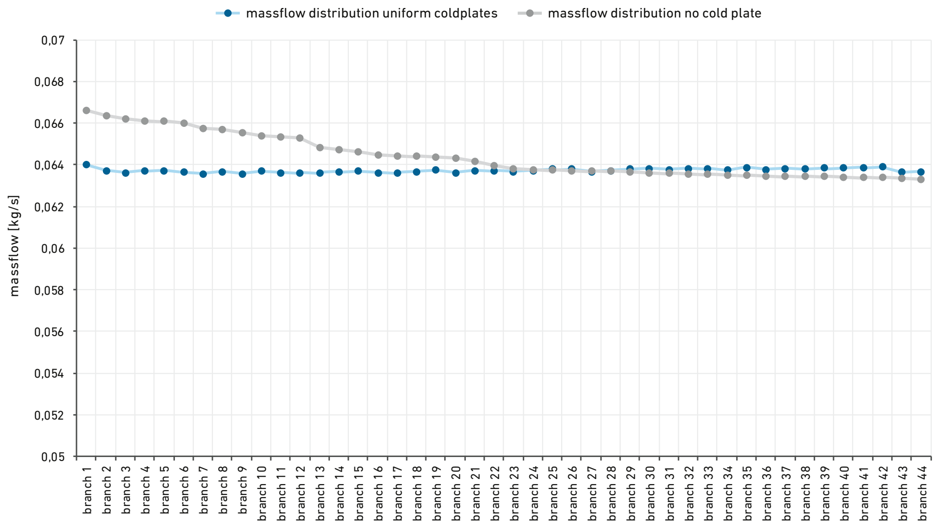
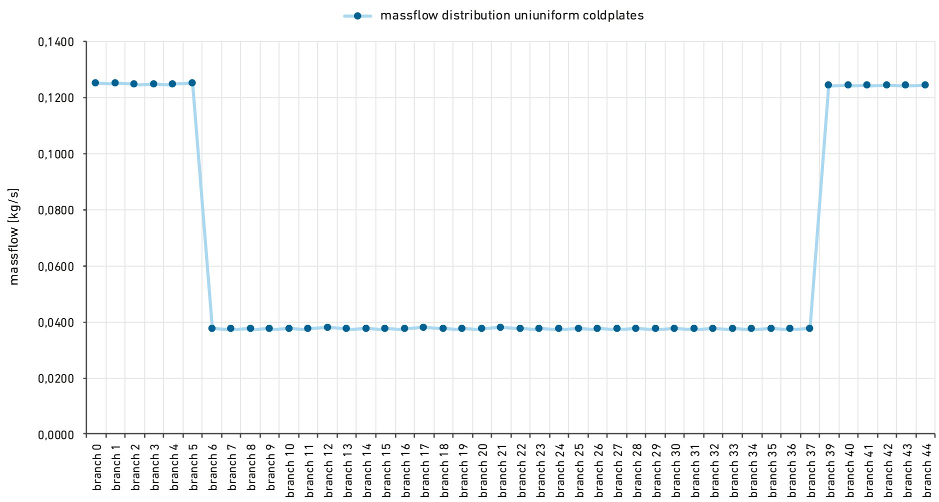


Figure 9: CFD simulation of a polymer manifold.

Impact of downstream hydraulic resistance on flow distribution



Unequal cold plate pressure loss across the branches



CFD modelling of the pressure loss of the cold plate

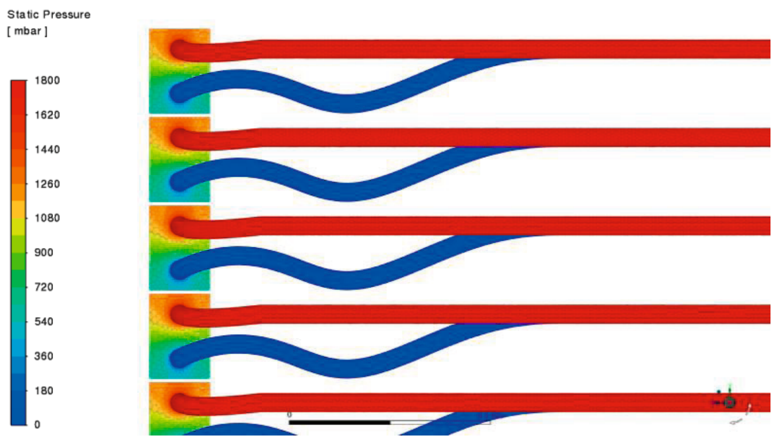


Figure 10: Impact of cold-plate hydraulic resistance on flow distribution. When the manifold is properly dimensioned, flow distribution is primarily governed by the hydraulic resistance of the downstream cold plates. From top to bottom, the CFD results show: mass-flow distribution without cold plates (grey) compared with identical cold plates on all branches (blue); the effect of unequal cold-plate resistance, with high resistance in branches 6–37 and low resistance in branches 1–5 and 38–44; and CFD modelling of the pressure drop through a cold plate.

The CFD simulation in Figure 7 confirms the estimated 20% lower pressure drop in the d63 circular polymer manifold compared to the 1.5-inch square steel manifold. Much of this pressure loss difference is driven by the hydraulic geometry of the assembly. The circular main section, integrated saddle couplings, and absence of coupling protrusions into the flow path result in a larger effective flow area, improved local pressure recovery, and smoother flow guidance through the manifold connections. This reduces local velocity peaks and minimizes unnecessary flow disturbances at the branch transitions, resulting in improved hydraulic efficiency and lower cooling system energy overhead.

Round polymer manifolds have a larger hydraulic diameter and reduced local velocity, resulting in ~20% lower pressure drop. Circular cross-sections are generally hydraulically advantageous because, for a given flow area, they minimize the wetted perimeter and thereby reduce friction losses. In addition, as pressure drop scales with the square of flow velocity, even relatively small changes in hydraulic diameter can lead to disproportionate changes in pressure drop and increased pumping energy requirements.

The other distinctive advantage of the polymer manifold is the positioning and geometry of the coupling interface. As illustrated in Figure 8, metal manifolds commonly use a thin coupling interface so that the couplings extend into the manifold cavity and partially obstruct the internal flow path. This protrusion reduces the effective flow area and limits the space available for the coolant to change direction smoothly within the manifold. The resulting local flow disturbance creates additional pressure drop, particularly at higher flow velocities where local restrictions increasingly influence hydraulic performance and pressure cascade stability. In contrast, the saddle design of polymer manifolds places the coupling externally, maintaining a smooth, unobstructed flow profile and avoiding cavities. Beyond reducing hydraulic resistance, this approach minimizes regions susceptible to biofilm formation and coolant contamination, supporting long-term coolant integrity and operational stability.

Regardless of manifold size or material, manifolds are typically designed to ensure uniform, predictable flow distribution so that each server receives the required cooling capacity. However, both internal CFD simulations and OCP testing indicate that downstream high-pressure-drop components act as hydraulic equalizers and dominate flow distribution behavior.[15] This was investigated using a CFD simulation of the configuration shown in Figure 5. The model used circular d63 supply and return manifolds with 44 branches (ITE ports), a volumetric flow rate of 170 l/min (44.91 GPM), and cold plates represented as porous domains with predefined hydraulic resistance. This model allows the simulation of any chassis configuration to gain insights into flow distribution, turbulence, and overall pressure drop.

In a properly sized manifold, the primary source of pressure loss is flow redirection or deflection (momentum change), where each branch behaves similarly to a reduced tee fitting as visualized in Figure 9. In a rack using such a well-dimensioned manifold, the cold plates act as the dominant hydraulic equalizers, resulting in fluctuations of less than 5%, regardless of the manifold design. However, variations in flow resistance, caused by inhomogeneous chassis or server configurations, can lead to uneven flow distribution.

These three scenarios are illustrated in Figure 10: (1) the manifold without downstream cold plates, (2) the manifold with identical downstream cold plates, and (3) the manifold with non-identical downstream cold plates.

As a design principle, GF aims to minimize pressure losses within the hydraulic conveyance system so that the ratio between infrastructure pressure drop and cold plate hydraulic resistance remains as low as possible. This preserves available pumping capacity for the components that drive thermal performance. For manifolds, this is defined as a total pressure loss per manifold, including saddle and flow redirection pressure losses of less than 50 mbar (0.73 psi). Based on this threshold, GF will recommend the correct manifold sizing to customers.

15 Open Compute Project, 2023, 10:23 min

5. Valve selection as the final step in hydraulic optimization

Just as with the manifold, other system components like valves can have a significant impact on the overall hydraulic performance and must be chosen thoughtfully. The performance and capability of valves are usually indicated by the Kv (Cv) value, also known as the flow coefficient. The valve selection should minimize avoidable hydraulic resistance while maintaining operational flexibility, pressure protection, and stable flow distribution throughout the cooling loop.

The Kv and Cv coefficients represent the flow of water through a valve at standardized temperatures of approximately 16–20°C (60–68°F): Kv in m^3/h at a pressure drop of 1 bar and Cv in US gal/min at a pressure drop of 1 psi. A higher Kv (Cv) value indicates a valve with lower resistance and greater flow capacity. The Kv (Cv) value forms the basis for proper valve selection that matches the desired flow requirements while minimizing pressure loss in the system. Choosing the right valve ensures that the system will operate efficiently within the system's design parameters and maintain optimal hydraulic performance. The simulation depicted in Figure 11 shows approximately 50% lower pressure loss for the full-bore valve design than for the reduced-bore dual ball valve at identical flow rates with PG25 at 30°C (86°F). The full-bore design has a Kv value of 34.2 m^3/h (Cv 39.5), compared with 25.4 m^3/h (Cv 29.4) for the reduced-bore design.

When specifying fluid couplings for water cooling systems, it is important to fully consider the materials of construction, both wetted and non-wetted. Particularly for coupling components exposed to the fluid flow path, materials should be chosen that are compatible with the fluid, thereby reducing the risk of corrosion, contamination, safety, and physical failure. Material selection can also be key to other system attributes, such as temperature, pressure, condensation, weight, and regulatory requirements, such as Restriction of Hazardous Substances (RoHS) (EU 2011) and UL94 (UL 2013). For sensitive environments, such as technology cooling systems (TCS) and datacom equipment cooling systems (DECS), coupling shutoff with minimal fluid spillage is recommended.[16]

Both steel and polymer valves can meet the required hydraulic and functional performance criteria. However, particularly for large quick connectors, additional factors may become decisive. Polymer quick connectors are significantly lighter than their steel counterparts, a difference that is further amplified because these connectors are typically designed as dual ball valves. This configuration effectively doubles the weight compared to a single ball valve, making the reduced mass of polymer designs a considerable advantage by greatly simplifying handling and installation.

16 ASHRAE Technical Committee 9.9, 2019

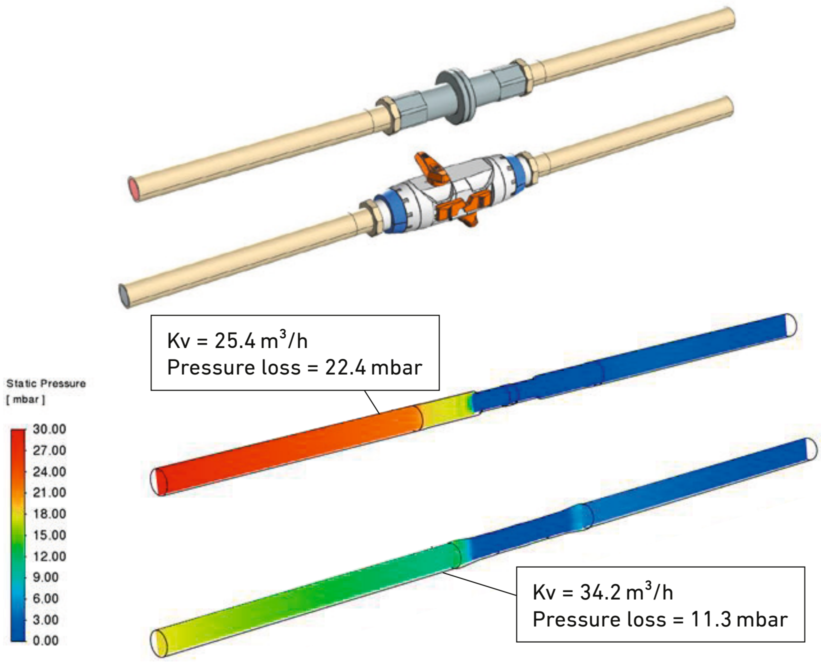


Figure 11: CFD simulation of a full-bore and a reduced-bore large quick connector

6. Local velocity effects and erosion risk in DLC systems

Erosion in pipes is the gradual loss of pipe material caused by the mechanical action of circulating fluid. When fluid velocity increases, the fluid's kinetic energy rises quadratically, increasing its potential to damage the pipe wall. Most severe damage occurs at elbows, tees, reducers, and valves where the flow changes direction. Particle impingement is the major cause of erosion[17] yet erosion can also occur through droplet impact.[18]

Abrasion, on the other hand, is the reduction in thickness of a pipe's inside surface material due to the mechanical action of erosion. In abrasive, low-to-moderate temperature and speed wet services, such as slurry transport lines, polymer pipelines have shown superior performance over other pipe materials.[19] In high-temperature, high-pressure applications, such as in power plant piping and chemical processing lines, steel piping is common, and the wall thinning is frequently observed due to an interlinked erosion-corrosion phenomenon[20].

Recently, the data center industry started paying increased attention to the topic of erosion, but with a focus on cold plate microchannels due to their sensitivity.[21 22] Today, DLC systems operate at lower fluid velocities, ranging from 1.5–2.1 m/s (4.92–6.89 ft/s), to protect these components, although an increase would be desired to intensify the cooling. In the presented simulation of Schneider Electric's EcoStruxure Reference Design 109, the maximum velocity in the pipework was 1.7 m/s (5.58 ft/s). For a piping system, this is still fairly low, considering that the generic recommendation for polymer piping goes up to 3 m/s (9.94 ft/s) at the pressure side. Furthermore, on the pressure side, higher velocities are still acceptable due to increased pressure, but are recommended to be controlled to avoid noise, vibration, and excessive wear[23].

However, in areas with higher fluid velocity combined with a change of direction, such as CDU outlets, erosion may present risks to piping that should be evaluated based on the specific medium, velocity, temperature, pressure, particle content, and local geometry. When comparing materials, polymers may offer advantages due to their immunity to corrosion and their well-documented resistance to abrasive wear. However, erosion mechanisms are highly complex and depend strongly on operating conditions, and the available research does not support a universal material ranking. Therefore, material selection for erosion resistance in critical locations should be evaluated on a case-by-case basis, and CFD simulations are recommended to identify and address potential erosion zones (Figure 12). Good hydraulic design reduces local acceleration, impingement, and unnecessary disturbances, thereby reducing erosion independent of material choice.

17 Madani Sani et al., 2019
18 Marzbali et al., 2023
19 Kirschmer et al., 2018
20 Bush, 1990
21 Squiller et al., 2016
22 Nerder, 2025
23 Georg Fischer, n.d.

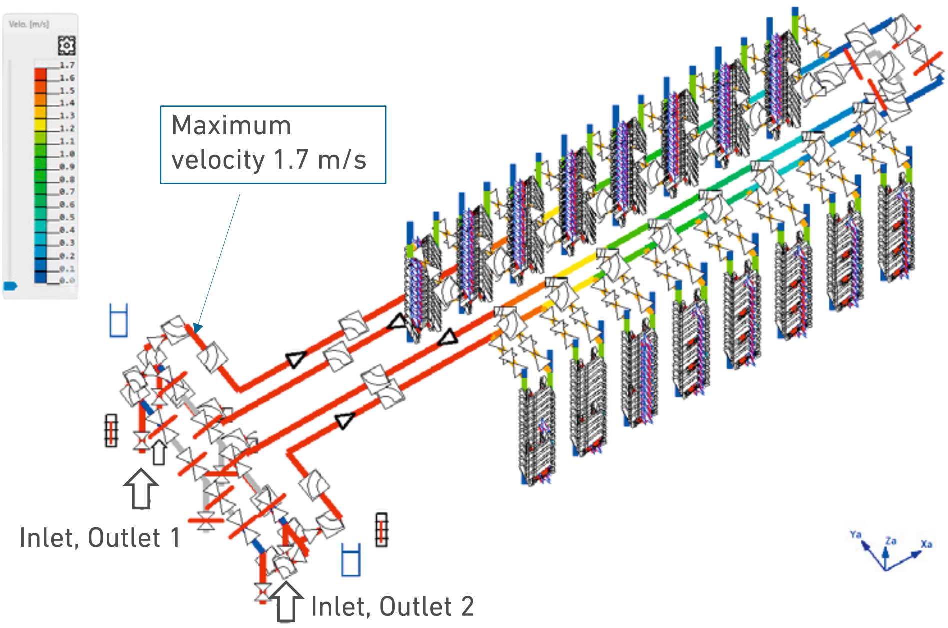


Figure 12: Fluid velocity analysis of Schneider Electric's EcoStruxure Reference Design 109

7. Hydraulic balancing is the key to predictable and stable hydraulic performance

Regardless of the material and the piping design, the eventual hydraulic performance depends on achieving the intended and predictable flow distribution through the cooling system. Even with appropriately sized pipes and acceptable pressure losses, cooling distribution and consequently cooling capacities can differ significantly. The general mechanism behind the variation is pressure loss differences within the system. Racks with a high pressure loss will experience a reduced volume flow compared to racks with a lower pressure loss. Consequently, if it is assumed that high-performance cold plates induce a higher pressure loss than standard cold plates, high-performance racks will receive a reduced volume flow corresponding to a reduced cooling capacity. This is contrary to the required performance and needs to be compensated for through hydraulic balancing.

In theory, the hydraulic location of a rack has an effect, too. However, since the racks have a significantly higher pressure loss than the distribution line, comparing the order of bar to mbar, the effect of the hydraulic location can usually be neglected. As illustrated in Figure 13, identical racks show an almost identical volume flow despite their differing hydraulic locations. This highlights that hydraulic balancing should primarily address pressure loss variations between cooling branches rather than their physical location within the distribution network.

To ensure hydraulically efficient cooling operation, uniform heat removal, and stable pressure conditions, hydraulic balancing must be conducted during commissioning. It represents the final step in translating a well-engineered hydraulic design into predictable thermal performance during operation.

In unbalanced systems, the overall cooling need is determined by the branch with the lowest available volume flow. To compensate for a reduced volume flow, the overall volume flow needs to be increased, leading to other racks being oversupplied. Ultimately, pumping energy demand rises without any thermal performance improvements, increasing the cooling system energy overhead. Hydraulic balancing addresses this by intentionally restricting excess flow in oversupplied branches (Figure 14).

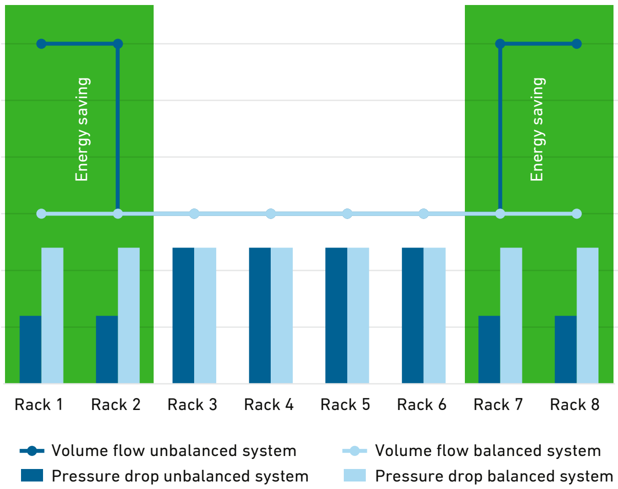


Figure 14: The effect of hydraulic balancing in a DLC system

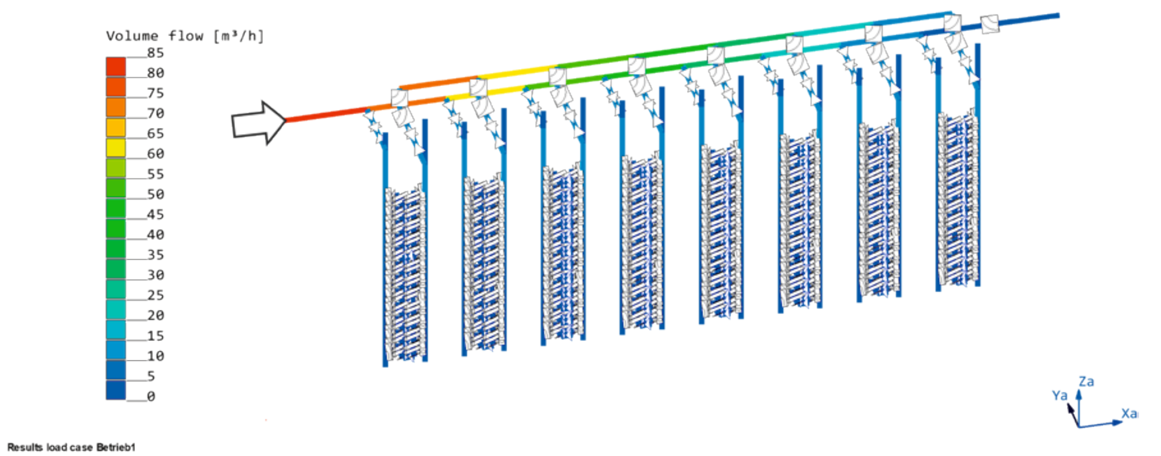


Figure 13: Racks show an almost identical volume flow despite differing hydraulic locations

This enables a reduction of the total volume flow and pumping energy demand at the CDU level, reducing cooling system energy overhead and contributing to improved PUE.

Under static operating conditions, balancing can be achieved with manual solutions. However, as visualized in Figure 15, the load during the day varies, and the full energy saving can only be achieved with automated optimization. In applications such as AI or HPC clusters, the thermal loads may change so rapidly that dynamic, pressure-independent balancing valves with fast control cycles are required to continuously adapt the flow to the cooling needs and maintain high system efficiency. Today, the state-of-the-art systems increasingly use digital control and advanced monitoring of flow, temperature, pressure, and energy to optimize hydraulic performance during operation. Such a system can save up to 20% of energy while extending the system's lifetime[24].

While current efforts focus on hydraulic balancing at the rack level, increasing rack densities may necessitate balancing at the server level in the future. In such a scenario, each server would be equipped with an individual balancing valve that dynamically regulates coolant flow according to the computing load.

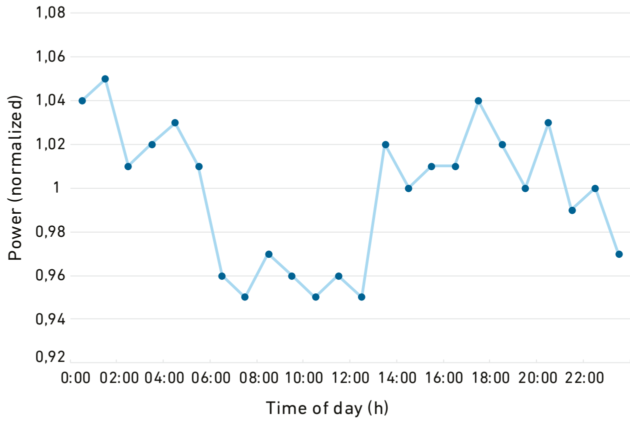


Figure 15: Computing load during the day[25]

24 Orozco & Schneider Electric, 2025
25 Radovanovic et al., 2021

8. Conclusion

Efficient direct liquid cooling is not achieved through isolated component selection; it emerges from a holistic, systemic consideration of engineered hydraulic interaction across the cooling loop. While cold plates remain the dominant thermal and hydraulic interface, the design of the surrounding fluid infrastructure determines pressure drop, pumping energy, coolant integrity, and long-term operational stability.

Achieving this performance requires more than selecting individual components. It requires an engineering methodology that combines hydraulic modeling, CFD validation, pressure management, and application-specific flow architecture design. Because pressure losses accumulate across pipes, fittings, manifolds, valves, couplings, and cold plates, every element contributes to the overall hydraulic behavior of the system. These capabilities enable cooling infrastructure to be dimensioned, validated, and deployed with predictable hydraulic performance and reliable long-term operation.

Hydraulic performance is ultimately the result of sound engineering rather than material selection alone. While steel pipes typically provide a larger internal diameter than polymer pipes of the same nominal size due to their thinner wall thickness, equivalent hydraulic performance can readily be achieved by appropriately dimensioning the polymer piping system based on the required internal flow area. Consequently, both polymer and steel systems can be engineered to deliver effective and energy-efficient hydraulic performance. In practice, material selection is therefore driven primarily by broader engineering and operational considerations, including installation efficiency, system weight, corrosion resistance, coolant integrity, joining technologies, maintenance, and lifecycle performance.

Appropriately engineered polymer piping systems support these objectives by enabling optimized coolant conveyance, reliable operation, and long-term system integrity. As liquid cooling scales across AI infrastructure, hydraulic engineering becomes an increasingly important discipline in determining cooling effectiveness, energy overhead, and infrastructure readiness.

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This publication forms part of the **GF Technical Series – Direct Liquid Cooling**, developed to provide engineers, consultants, OEMs, and data center operators with practical guidance on the design of reliable and energy-efficient cooling infrastructure.

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