White Paper

[Water management in Data Centers]

***At a glance**. Modern data centers face rapidly increasing cooling demands due to higher server densities, especially from AI and high-performance computing, making water-based cooling essential for efficient heat removal. Water's high specific heat capacity makes it a superior thermal vector, but its intensive use introduces vulnerabilities linked to water quality and system reliability. Cooling circuits – comprising exchangers, cooling towers, and piping – are susceptible to microbial growth and biofilm formation on internal surfaces, which can reduce heat transfer, raise energy use, and accelerate corrosion. Traditional water-quality measures often miss surface biofilm, so continuous, intelligent monitoring is crucial. The paper highlights advanced cooling technologies from cooling towers to direct-to-chip and immersion systems, with a focus proactive water treatment combining chemical, physical, and biofilm detection strategies. ALVIM Biofilm Sensors provide real-time surface-specific detection, enabling early interventions, optimized biocide use, reduced operational costs, and improved thermal performance. Proactive biofilm management is a key to stable, energy-efficient data center operation.*

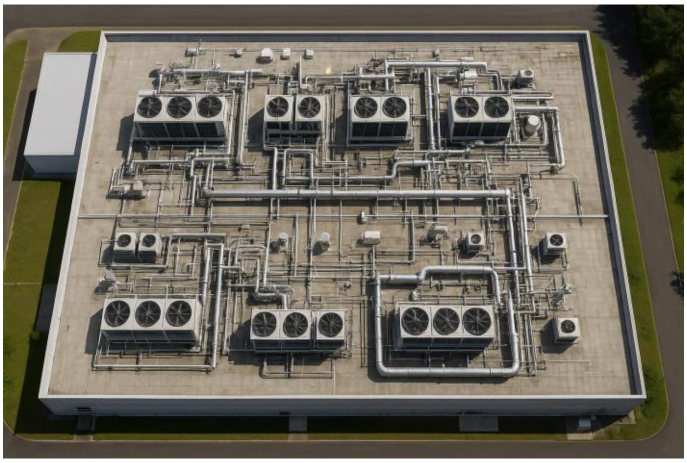

Figure 1: Data center

In today's digital landscape, data centers represent the critical infrastructure supporting every data-driven activity. The global demand for computational power is rapidly increasing, driven by the expansion of cloud services, the digitalization of industrial processes, and, above all, the widespread adoption of computation-intensive technologies such as artificial intelligence (AI). As a result, power densities within data center racks have risen sharply, with AI-dedicated systems already exceeding the thresholds that can be effectively managed through air cooling alone. This shift is accelerating the adoption of liquid-based cooling technologies. Solutions such as evaporative cooling towers, high-efficiency chiller loops, in-row or in-rack air-to-water heat exchangers, and especially direct-to-chip liquid cooling are becoming industry standards for managing rack densities above 80 kW, and up to 200 kW in advanced configurations. The power density of server racks, particularly those dedicated to AI workloads, has grown dramatically in recent years, transforming cooling from a simple engineering requirement into a true technological challenge. In this context, water has become the most effective thermal vector available to the industry, thanks to its specific heat capacity more than 3,500 times higher than that of air. However, the increasingly intensive use of water also introduces operational vulnerabilities that cannot be overlooked. Water quality affects not only the energy efficiency of the cooling infrastructure, but its overall reliability.

Water management into Data Centers

In the thermal management of a data center, water is the most effective medium for transporting the heat generated by servers. Figure 2 below clarifies the way this liquid flows throughout the cooling infrastructure, showing how the entire system relies on a continuous sequence of tightly coordinated thermal transformations. At the core of the systems are servers, which release heat into the environment and warm the surrounding air. This warm air is drawn in and directed toward an air-

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handling unit, where a water-based heat exchanger removes the excess thermal energy. As the water inside the exchanger absorbs heat, it flows through the circuit toward an air-handling unit, where a water-based heat exchanger absorbs heat. The liquid flows through the circuit toward the outside of the building and reaches the cooling tower. Here, the heat that has been collected is dissipated through the principle of evaporation – part of the water releases its latent heat to the moving air and becomes cooler. The diagram shows how the cooling tower functions as a natural dissipator as explained in a previous paper. Warm water enters from the top, it is sprayed inside the tower where it comes into contact with an upward airflow that enhances evaporation and cooling. The cooled water is then collected in the basin at the bottom and pumped back into the system, returning to the heat exchanger inside the data center and closing the loop. At the same time, Figure 2 highlights the airflow within the server room – identified in the diagram by the thicker blue and red arrows. The cooled air supplied by the system passes through the racks, absorbs heat, warms up, and returns to the conditioning area. This dual air-water circuit works in synergy to ensure stable server temperatures and uninterrupted operation of the entire infrastructure.

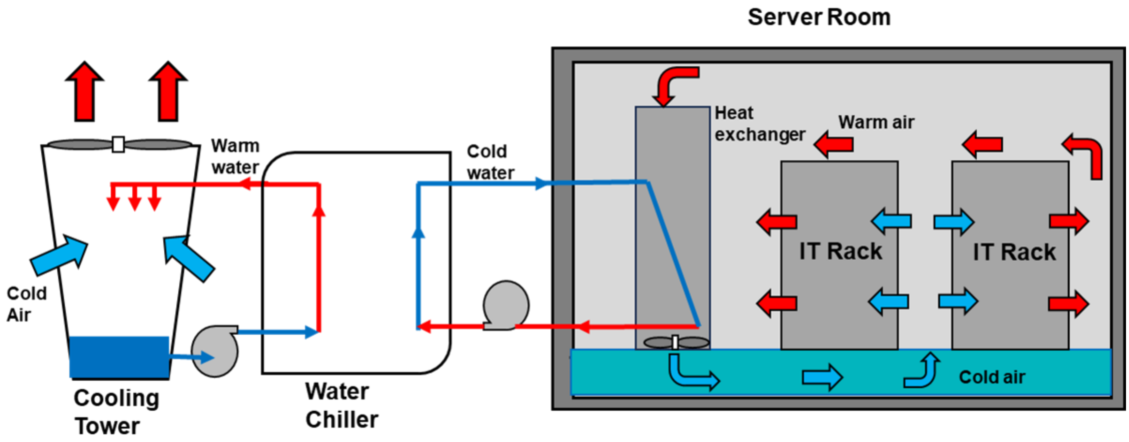

Figure 2: Diagram of the operation of cooling water in data centers

Although the process appears linear, every part of the water circuit represents a potential point of vulnerability. The inner surfaces of pipes, basins, and heat exchangers are ideal environments for the formation of a bacterial layer usually known as “biofilm”. As widely demonstrated, even a very thin layer can significantly impair cooling capacity, increasing energy demand and placing additional stress on the cooling equipment. Understanding the water pathway, as summarized in the diagram, makes it easier identify the critical points where biofilm monitoring becomes essential. Every component, from the cooling tower to the heat exchanger creates conditions where microbial growth can thrive and compromise the thermal stability of the entire data center. For this reason, continuous and intelligent monitoring of water quality is no longer optional, but a fundamental requirement for ensuring stable performance, reducing operational costs, and extending the lifespan of the infrastructure.

Table 1 below summarizes and compares the main cooling technologies used in data centers, highlighting their operating principles, key advantages, and typical application scenarios. The table provides a coherent overview of the evolution of cooling solutions, directly reflecting the increasing power density of IT workloads and the gradual transition from air-based systems to increasingly advanced liquid cooling technologies. As shown in the table, facility-level cooling technologies such

Cooling emerges as a strategic enabler, essential for ensuring performance, sustainability, and long-term scalability of future data centers

as cooling towers and chiller-based systems play a fundamental role in rejecting the overall thermal load of the data center. Evaporative cooling towers, identified in the table as highly energy efficient solutions, are particularly well suited for medium and large data centers where large scale heat dissipation is required. Chiller-based refrigeration loops, also described in the table, operate as closed systems and provide precise control of supply water temperature, making them a preferred choice for high-availability and mission-critical environments. The table further illustrates how, at the IT room level, in rack cooling solutions introduce a more targeted approach to thermal management, making them suitable for medium to high density data centers. The heat exchanger captures the thermal energy of the exhaust air at the source, reducing the load on CRAC (Computer Room Air Conditioner) systems and enabling support for high-density racks without major structural modifications. Furthermore, direct-to-chip liquid cooling represents a key enabler for the most demanding computational workloads. By delivering water directly to CPUs (Central Processing Units) and GPUs (Graphics Processing Units) through cold plates, this technology achieves maximum thermal efficiency and support rack power densities exceeding 80-200 kW, making it particularly suitable for AI systems, HPC (High Performance Computing) environments and supercomputing applications. The most advanced technology shown in the table is immersion cooling, in which servers are fully immersed in dielectric fluids. This approach enables extreme thermal performance and very high-power density while reducing the number of moving parts, and this is therefore well suited for high-end AI and HPC. Overall, the table clearly illustrates the relationship between computational requirements, power density, and cooling architectures. In this context, cooling emerges as a strategic enabler, essential for ensuring performance, sustainability, and long-term scalability of future data centers.

Technology	Description	Key advantages	Applications
Cooling Tower	Rejects heat through evaporative water cooling in the primary circuit	High energy efficiency, suitable for large thermal management	Medium/large data centers
Chiller / Refrigeration Loop	Closed system using refrigerants to maintain constant water temperature	Precise cooling control, integration with free cooling	High-availability data centers
In-row / In-rack cooling	Air-to-water heat exchangers installed between or inside server racks	Hot spot mitigation, modular thermal management	Medium-to-high density data centers
Rear Door Heat Exchanger (RDHx)	Heat exchanger mounted on the rear door to cool warm exhaust air	Low load on CRAC	Data centers with high-density racks
Direct-to-Chip Liquid cooling	Water delivered directly to CPU and GPU through cold plates and microchannels	Maximum thermal efficiency, supports > 80-200 kW / rack	AI systems, HPC, supercomputers
Immersion cooling	Servers fully immersed in dielectric fluid	Extreme performance, very high density, fewer moving parts	High-end HPC, extreme AI workloads

Table 1. Main cooling technologies in Data Centers

Water treatment processes in Data Centers

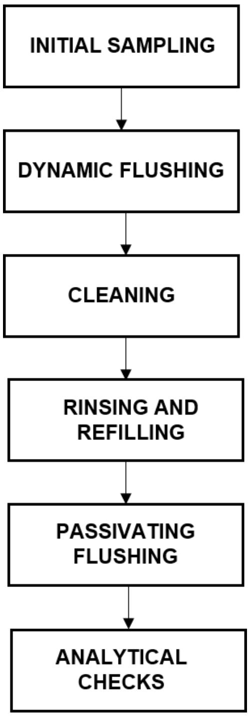

Figure 3: Scheme of water treatment for data centers cooling

In modern data centers, water treatment within cooling circuits follows a tightly regulated sequence of operations designed to ensure thermal efficiency while preventing corrosion, scaling, and microbiological proliferation. The process typically begins with initial sampling and comprehensive chemical-microbiological diagnostics, followed by dynamic flushing and cleaning cycles using alkaline or surfactant-based detergents, combined with broad-spectrum biocides to remove existing deposits. Subsequent steps include system draining, rinsing, and refilling, with the addition of alkalizing or acid-based descaling additives under controlled pH conditions to eliminate oxidation residues and stabilize metallic surfaces in order to avoid corrosion. Final phases involve passivating flushing procedures with molybdate-based inhibitors to promote the formation of protective anticorrosive layers, accompanied by routine analytical checks to verify chemical balance, microbial load, and absence of biofilm regrowth. Indeed, among the main risk factors emerging in modern cooling circuits is the formation of biofilm. Biofilm is a complex aggregate of microorganisms embedded in a self-produced polysaccharide matrix capable of firmly adhering to the internal surfaces of pipes, heat exchangers, and hydraulic components. Unlike free-floating bacteria, biofilm behaves as a protected and resilient micro-ecosystem, with resistance to biocides up to 1000 times higher. Its ability to thrive in environments with minimal nutrients, moderate temperatures, and low turbulence makes it particularly problematic in data center water circuits. From a thermal perspective, a biofilm layer as thin as 20 µm can reduce heat transfer efficiency by 30%, significantly increasing the energy consumption of cooling systems. In direct-to-chip liquid cooling systems – where channels and microchannels have extremely small cross-sections – biofilm can cause clogging, flow reduction, pump overload, and even overheating of critical chips. In evaporative cooling towers, in addition to efficiency losses, biofilm creates an environment favorable to the growth of pathogens such as *Legionella pneumophila*, introducing potential health risks and regulatory liabilities for operators. Without continuous, targeted monitoring, biofilm growth becomes a progressive phenomenon that often goes unnoticed until severe problems arise: decreased cooling performance, increased water consumption, accelerated corrosion (MIC, Microbially Influenced Corrosion), as well as rapidly rising operational and maintenance costs. For these reasons, modern data centers are increasingly recognizing the importance of advanced water-management strategies based on predictive diagnostics, in which dedicated biofilm detection represent a strategic technology. Unlike traditional water-quality parameters (turbidity, redox potential, residual biocide concentration), biofilm sensors provide a direct, real-time, and surface-specific measurement of biological growth, enabling timely and precise corrective actions. Biofilm monitoring is therefore an essential element to ensure cooling-system continuity, reduce environmental impact, optimize water usage, and extend the lifespan of mission-critical infrastructures. Water treatment typically starts with chemical conditioning, which aims to maintain the right balance between corrosion inhibition, scale prevention, and microbiological control. Corrosion inhibitors – often based on phosphates, molybdates, or organic films – are introduced to protect metal surfaces from oxidation and pitting, particularly in systems containing steel, copper, or aluminum components. Scale inhibitors, on the other hand, prevent the precipitation of calcium, magnesium, and silica, which would otherwise coat heat-exchange surfaces and significantly reduce thermal performance. However, one of the most critical aspects of water treatment in data centers is biological control. Microorganisms naturally present in water can proliferate rapidly, especially in warm, nutrient-rich environments such as cooling towers or low-velocity areas of pipework. If left unchecked, these microorganisms form biofilm – as discussed above. This is where biocides play a central role, as discussed in a previous white paper. Biocides are chemical substances designed to eliminate or inhibit the growth of microorganisms. Data centers typically use a combination of oxidizing biocides (such as chlorine, bromine, or chlorine dioxide) and non-oxidizing biocides that attack microbial metabolism in complementary ways. Alternating different classes of biocides helps avoid resistance and ensures broader microbiological coverage. In addition to chemical treatments, mechanical and physical processes are also widely used. Filtration systems remove suspended solids that can act as microbial nutrients or seed deposits inside heat exchangers. Side-stream filters continuously process a portion of the circulating water, preventing the gradual accumulation of particulates. Some facilities also adopt ultraviolet (UV-C) disinfection to reduce microbial load without adding chemicals, while others use magnetic or electrochemical systems to mitigate scale formation. Despite the widespread adoption of these methods, traditional water treatment has structural limitations. Most of the measurements usually carried out (conductivity, pH, biocide residuals, turbidity, etc.) just focus on the liquid phase, without paying any attention to what is happening on the surfaces of hydraulic components. Here the root cause of most microbiological issues can be found. Indeed, only 10% of bacteria live free in the water, while 90% is attached to surfaces. Biofilm monitoring can support operators in detecting this biological phenomenon before changes in water quality or system performance make it visible. This enables targeted interventions, reduces excessive chemical use, and helps maintain continuous, energy-efficient operation of the cooling system. In a sector where even a slight increase in thermal resistance can translate into substantial energy costs, proper water treatment is not simply a maintenance task. Continuous and intelligent monitoring of cooling water system is now a fundamental requirement for ensuring stable thermal performance, reducing operational costs, and extending the lifespan of the data center’s cooling infrastructure.

Continuous and intelligent monitoring of cooling water system is now a fundamental requirement

Biofilm monitoring in Data centers

ALVIM Sensors represent an advanced technological solution for modern data centers, providing direct, real-time, and surface-specific monitoring of biofilm formation within water circuits. Unlike traditional water quality parameters such as turbidity, redox potential, or residual biocide concentration, which only provide indirect indications about microbiological proliferation, ALVIM Sensors detect bacterial growth exactly where it matters, on the internal surfaces of pipes and other critical hydraulic components. This direct monitoring enables early identification of biofilm development, long before it becomes visible or affects system performance. By detecting biofilm at its initial stages, operators can implement precise corrective actions, such as targeted biocide dosing, mechanical cleaning, or flow adjustments. This smart approach allows to prevent thermal efficiency loss, energy overconsumption, and accelerated corrosion. ALVIM Sensors provide continuous insights into the biological state of the system, allowing predictive and proactive water management. This approach optimizes chemical usage, reduces environmental impact, and extends the operational lifespan of mission-critical infrastructure. In high-density cooling scenarios, such as AI servers or HPC clusters, where even small increases in thermal resistance can significantly impact energy efficiency, integrating ALVIM Technology offers a tangible competitive advantage. By

ALVIM Sensors provide continuous insights into the biological state of the system, allowing predictive and proactive water management

Figure 4: ALVIM Biofilm Sensors

complementing conventional water treatment strategies, ALVIM Sensors transform water management from a reactive task into a proactive, intelligent system, ensuring uninterrupted operation, stable cooling performance, and long-term reliability in increasingly demanding technological environments.

Conclusions

The rapid increase in power density and thermal load in modern data centers – driven by AI, HPC, and other computation-intensive applications – has made water-based cooling systems a critical element for operational continuity and energy efficiency. Despite well-established chemical and mechanical water-treatment strategies, biofilm formation on internal surfaces remains a persistent risk factor, capable of reducing heat transfer efficiency, increasing energy consumption, accelerating MIC, and raising operational costs. ALVIM Sensors provide a technically advanced solution to this challenge, enabling real-time monitoring of biofilm formation. By detecting microbial growth at its earliest stage, these probe allow operators to implement predictive and targeted interventions, optimizing biocide dosing, maintenance cycles, and hydraulic performance. This reduces unnecessary chemical use, minimizes environmental impact, and ensures the thermal stability of the system even under high-density conditions. From a technical perspective, integrating ALVIM Technology into the water-management framework transforms reactive maintenance into a data-driven, proactive strategy, improving system reliability, extending the lifespan of heat exchangers and piping, and preventing performance degradation before critical thresholds are reached. In brief, ALVIM Biofilm Sensors represent a strategic technological enabler: they complement conventional water-treatment approaches, provide actionable surface-level insights, and ensure stable, energy-efficient, and resilient cooling system operation in high-performance, high-density data center environments.

Do you have a similar problem with biofilm? Contact our experts and ask for a free custom-tailored consultancy, you will receive further information about ALVIM products and services.

The ALVIM Biofilm Monitoring System is a reliable tool for the early detection of bacterial growth on surfaces, on-line and in real time, in industrial production lines, cooling water systems, etc.

The ALVIM Technology has been developed in collaboration with the Italian National Research Council, Institute of Marine Sciences, and it is currently used worldwide in many different application fields.

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