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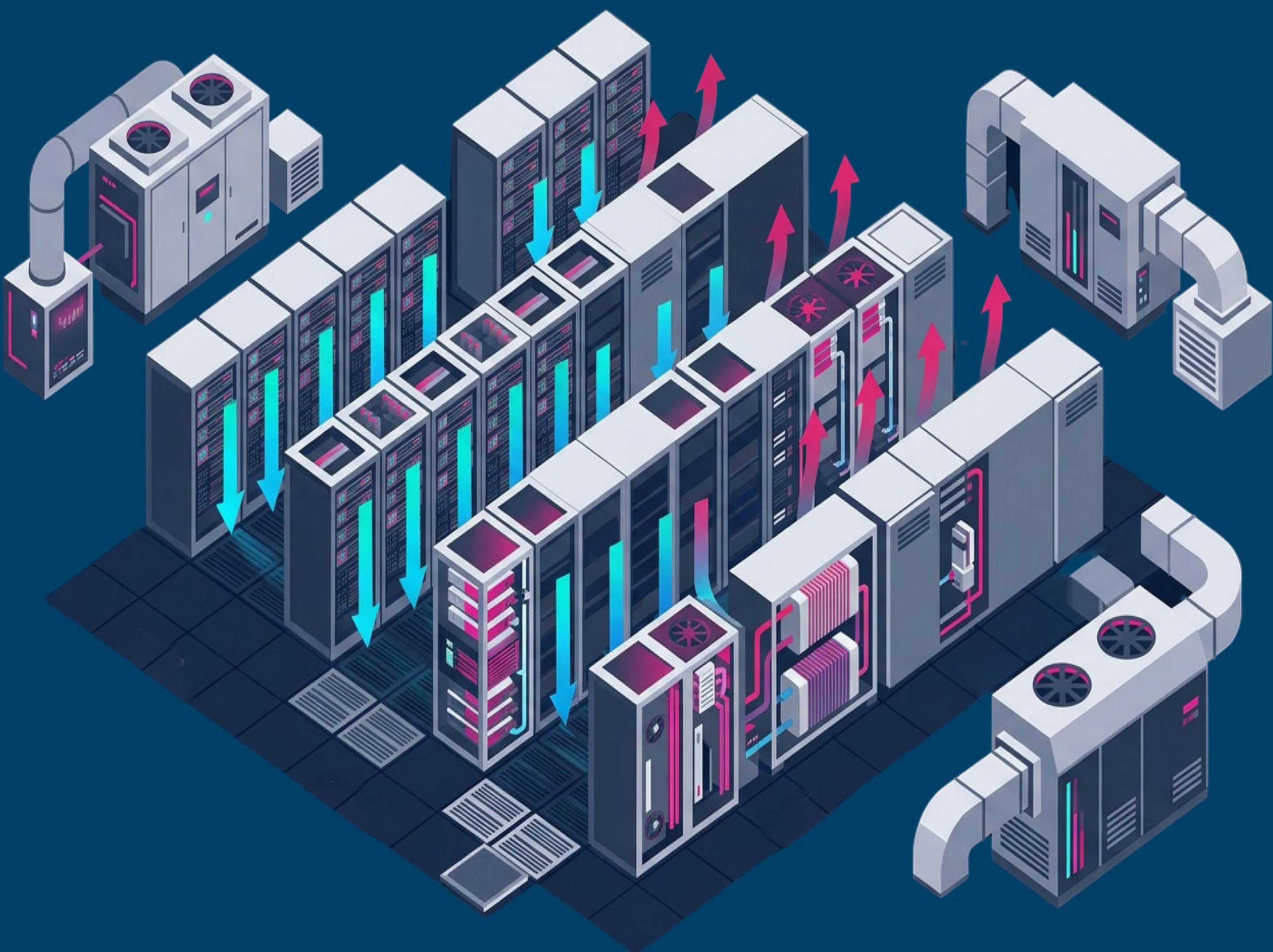
Cool to Prevent Failure

Applied Psychrometrics, Cooling Technologies and Airflow Management: The Complete Guide to Data Center Cooling Systems



Introduction

Heat is the number one silent enemy of hardware in a data center. Unlike a power outage, which causes an immediate shutdown, thermal failure acts progressively: it raises component temperatures, shortens their lifespan, causes intermittent errors, and ultimately shuts down the system due to thermal protection or permanent damage.

The cooling system accounts for between 30% and 40% of total energy consumption in many data centers. Together with the electrical system, it is the subsystem with the greatest impact on availability and operational efficiency. However, its technical complexity also makes it one of the most frequently poorly designed, undersized, or misoperated systems.

This e-book covers the complete discipline of data center cooling: from the fundamentals of psychrometrics that define operating conditions, to the most advanced free cooling and airflow management technologies. It is aimed at technically-grounded professionals who want to understand the system in depth, not just operate its controls.

What you will find in this e-book

- Applied Psychrometrics: DB, WB, dew point
- Why comfort air conditioning kills servers
- ASHRAE ranges: temperature and humidity for IT equipment
- The 5 main cooling technologies
- Free Cooling: direct and indirect
- Airflow management and hot/cold aisles
- Aisle containment: the most impactful efficiency practice
- Rack density and its relationship to the cooling system

Applied Psychrometrics in the Data Center

Psychrometrics is the branch of physics that studies the thermodynamic properties of moist air. In a data center context, three psychrometric quantities are fundamental to correctly understanding and designing the cooling system: dry-bulb temperature (DB), wet-bulb temperature (WB), and dew point (DP).

The Dew Point: The Limit That Cannot Be Crossed

Quantity	Symbol	Definition	DC Relevance
Dry-Bulb Temperature	DB	Air temperature measured with a conventional thermometer unaffected by humidity	The main reference for IT equipment operating ranges. Most commonly used in manufacturer specifications
Wet-Bulb Temperature	WB	Minimum temperature achievable through water evaporation. Always equal to or lower than DB	Combined indicator of temperature and humidity. Used to evaluate evaporative cooling systems
Dew Point	DP	Temperature at which water vapor reaches 100% RH and begins to condense	Critical limit: if the surface of a component is below the DP, condensation forms and there is a risk of short circuit

The Dew Point: The Limit That Cannot Be Crossed

The dew point is the most critical psychrometric parameter from an operational standpoint. When the temperature of any surface in the server room drops below the dew point, water vapor in the air condenses on that surface. If that surface is an electronic circuit, a memory card, or a connector, the result is an immediate short circuit or accelerated condensation corrosion.

Maximum Dew Point Value

The maximum allowable dew point in the server room is 15°C, according to ASHRAE TC 9.9 guidelines. A dew point above 15°C significantly increases the risk of exceeding 60% RH, with the resulting risk of corrosion and condensation inside equipment. This value must be monitored in real time, not inferred from temperature and RH.

Essential Thermal Unit Conversions

A data center cooling system works with several units of measurement that must be handled fluently to correctly interpret equipment specifications and thermal balances:

Conversion	Result	Typical Use
1 W	3,41 BTU/h	Convert server power consumption (W) to heat to be dissipated (BTU/h)
1 W	0,000284 RT	Express thermal load in refrigeration tons
1 kW	3.412 BTU/h	Sizing CRAC/CRAH systems
1 RT	12.000 BTU/h	Capacity of cooling units in the American market
1 CFM	Area (ft^2) × air velocity (ft/min)	Calculating room airflow rate

ASHRAE Ranges — What Temperature Should Your Data Center Maintain

One of the most widespread misconceptions among data center operators is what temperature should be maintained in the server room. The answer is not intuitive: room temperature is an incomplete indicator. What matters is the air inlet temperature to IT equipment, which is the variable ASHRAE regulates.

Thermal Operating Ranges for Class A1 Equipment

Parameter	Recommended Range	Allowed Range	Condition
Inlet Temperature (DB)	18°C – 27°C	15°C – 32°C	Allowed range only for short periods
Relative Humidity	40% – 60%	8% – 80%	Allowed range only for short periods
Maximum Dew Point	– 9°C a 15°C	−12°C a 17°C	Do not exceed 15°C in continuous operation
Maximum Temperature Change	5°C/hour	5°C/hour	To avoid thermal stress on components
Maximum Altitude	950 m	3.000 m above sea level	Above this altitude requires power derating

The ASHRAE Energy Opportunity

The revision of the ASHRAE guidelines extended the recommended range up to 27°C at the equipment inlet. This allows raising the supply temperature of the cooling system, which has a direct impact on efficiency: each degree increase in supply temperature can represent between 2% and 4% savings in cooling system energy consumption. Data centers operating at 18°C are leaving money on the table.

Where to Measure Temperature

Temperature must be measured at the air inlet of each IT device, not in the cold aisle or the room in general. The cold aisle temperature can differ significantly from the actual inlet temperature if there is hot and cold air mixing, mispositioned perforated panels, or raised floor leaks. Rack-level temperature monitoring, at the front of each IT unit, is the only operationally valid measurement.

Precision vs. Comfort — Why Conventional Air Conditioning Is Not Suitable

One of the most common mistakes in small installations or improvised server rooms is using comfort air conditioning units (designed for people) to cool IT equipment. The differences between the two systems are so fundamental that this decision can completely compromise equipment availability.

Feature	Comfort A/C	Precision A/C (CRAC/CRAH)	Operational Impact
Airflow	< 100 CFM/kW (insufficient)	>= 158 CFM/kW	Comfort A/C does not move enough air to dissipate server heat
Sensible Heat Ratio (SHR)	<= 70%	> 90%	Comfort A/C 'wastes' capacity on dehumidification instead of cooling
RH Control	None or very basic	Precise humidification and dehumidification	Without RH control, risk of ESD or corrosion
Internal Redundancy	No redundant components	Redundant compressors, fault-tolerant	Comfort A/C is not designed for 24/7 operation
Response Speed	Slow	Fast, responds in seconds to load changes	Servers generate sudden heat spikes that comfort A/C cannot handle

The Real Cost of Comfort A/C in a Server Room

A comfort A/C system operating in a server room is not just inefficient: it is actively dangerous. Its inability to move sufficient airflow guarantees hot spots in racks, its lack of precise RH control generates ESD or corrosion risks, and its absence of redundant components turns any failure into a critical event.

Cooling Technologies — From Direct Expansion to Free Cooling

The market offers multiple technologies for data center cooling, each with its own advantages, limitations, and optimal application ranges. Choosing the right technology depends on the power to be dissipated, rack density, geographic location, water availability, and energy efficiency goals.

Direct Expansion (DX) — Base Technology

Direct Expansion systems use a refrigerant circuit that absorbs heat from the room directly in the CRAC unit, compresses it, and expels it outside through a condenser unit. It is the most widespread technology in small and medium-sized installations.

- Indoor component: CRAC unit (Computer Room Air Conditioner), which contains the compressor, evaporator, and controls.
- Outdoor component: condenser unit, which rejects heat to the outside via air.

- Main advantage: relatively simple installation, no chilled water plant required.
- Main limitation: efficiency drops significantly when outdoor temperature is high; not the most efficient option for large power loads.

Chilled Water (Chiller) — The Solution for High Power Loads

Chilled water systems separate the cooling process into two independent circuits: the primary chilled water circuit, which distributes cooling to CRAH units in the server room, and the secondary heat rejection circuit, which dissipates heat to the outside via cooling towers or condensers.

- Main component: chiller, which produces chilled water via compression or absorption.
- Room distribution: CRAH units (Computer Room Air Handlers), without their own compressor, which exchange heat with the chilled water.
- Heat rejection: cooling towers, evaporative condensers, or air-cooled condensers.
- Main advantage: greater efficiency at scale, possibility of integrated free cooling, centralized maintenance.
- Limitation: greater complexity, higher initial investment, requires water treatment system.

CRAC vs. CRAH: The Difference That Defines the System

CRAC (Computer Room Air Conditioner): has an integrated compressor. Self-contained system, typical of DX installations. CRAH (Computer Room Air Handler): no compressor. Only exchanges heat with the chilled water supplied by the chiller. More efficient in large installations, but dependent on the chilled water system. The distinction is critical for understanding the cooling system architecture.

Free Cooling — Cooling Without Compressors

Free cooling is the highest-impact strategy for energy efficiency in modern data centers. Its principle is simple: instead of using compressors to produce cooling, it takes advantage of outdoor conditions when the ambient temperature is low enough to dissipate heat without mechanical refrigeration.

There are two modes with very different characteristics:

Mode	Principle	Advantage	Limitation
Direct Free Cooling (Airside)	Introduces cold outdoor air directly into the room in a single pass	Maximum efficiency. No intermediate heat exchanger. Minimum operating cost	Outdoor air comes into direct contact with equipment: requires thorough filtration. Only viable when outdoor air quality is acceptable
Indirect Free Cooling	Outdoor air cools the primary circuit water through a heat exchanger. Air does not enter the room	Outdoor air never contacts equipment. Valid in environments with outdoor contamination. Compatible with existing chiller systems	Lower efficiency than direct due to heat exchanger losses. Higher initial investment

The number of hours per year that free cooling can be activated (economizer hours) depends on the climate of the location. In temperate climates of northern Europe, free cooling can cover more than 70% of annual hours. In warm Mediterranean or tropical climates, the percentage is significantly lower.

InRow Cooling — Bringing Cold to the Rack

InRow units are an evolution from room-level cooling to row-level cooling. Instead of distributing cold air from perimeter or ceiling units, InRow units are installed directly between racks, supplying cold air exactly where it is needed and collecting hot air without long travel distances.

- Main advantage: virtually eliminates hot and cold air mixing. Very effective for high rack densities (> 10 kW/rack).
- Room design: compatible with both raised and flat floors.
- Limitation: greater number of units to manage and maintain. Higher initial cost per unit of power.

Direct Liquid Cooling — The Future for High Density

For rack densities above 20 kW/rack, air as a heat transfer medium is no longer sufficient. Direct Liquid Cooling brings the refrigerant liquid to the server itself, exchanging heat directly at the CPU, GPU, or memory cards. There are two approaches:

- Rear-door heat exchanger: heat exchanger integrated into the rear door of the rack, which captures heat from the exhaust air before it exits to the hot aisle.
- Direct liquid to chip: the liquid circulates through cold plates attached directly to the processors. Maximum efficiency but requires equipment specifically designed for it.

Airflow Management — The Most Impactful Efficiency Practice

Having the right cooling capacity is a necessary but not sufficient condition. If cold air does not reach IT equipment inlets efficiently, and if hot air mixes with cold before being evacuated, the cooling system works twice as hard to achieve half the result. Airflow Management is the discipline that solves this problem.

The Three Physical Principles of Airflow

- Cold air is denser than hot air: hot air naturally rises and cold air tends to sink. The distribution system design must take advantage of this behavior, not fight it.
- Heat must be removed from the server room: if heat is not efficiently evacuated, it accumulates and recirculates, progressively raising the inlet temperature to equipment.
- Airflow is as important as cooling capacity: cold air alone does not cool equipment if it does not reach the inlet at the same rate it is consumed. Airflow rate (CFM) is as critical as the supply air temperature.

Cold Aisle / Hot Aisle — The Industry Standard

Arranging equipment in alternating hot and cold aisles is the most widespread airflow management practice, supported by TIA-942 and BICSI-002 standards. Its logic is simple: all racks in a row orient their front (cold air intake) toward the same aisle, and their rear (hot air exhaust) toward the opposite aisle.

Minimum aisle dimensions are:

- Cold aisle: minimum 4 feet (approx. 1.2 meters) wide.
- Hot aisle: minimum 14 feet (approx. 4.3 meters) wide to facilitate heat evacuation.

Why the Cold/Hot Aisle Works

Without this arrangement, hot air exhausted from the rear of racks can be drawn into equipment in the facing rack, creating a recirculation loop that progressively raises the inlet temperature. With alternating aisles, cold and hot air have physically separated paths, eliminating mixing and allowing the cooling system to operate much more efficiently.

Aisle Containment — The Next Level of Efficiency

Aisle containment takes the hot/cold aisle concept to its logical conclusion: if the separation between cold and hot air is good, physically containing one of the two aisles is even better. There are two approaches:

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Approach	What Is Contained	How It Works	Relative Efficiency
Cold Aisle Containment (CFCC)	The cold aisle is enclosed with panels and doors	All cold air from the raised floor goes directly to the rack inlets, with no possibility of mixing with hot air	High. Allows raising supply temperature while maintaining equipment inlet temperature
Hot Aisle Containment (HCCC)	The hot aisle is enclosed and connected directly to the CRAC/CRAH unit returns	Hot air goes directly to the return without circulating through the room. Maximum control of return temperature	Very high. It is the most energy-efficient configuration in most scenarios

Implementing aisle containment is, in terms of energy return on investment, one of the most cost-effective measures available in an existing data center. In installations with significant air mixing, it can reduce cooling system energy consumption by 15% to 30%.

Three Cold Air Distribution Methods

Method	How It Distributes Air	Floor Type	Typical Use Case
Underfloor	The raised floor acts as a plenum. Perforated panels in the cold aisle direct air toward the racks	Raised floor required	The most widespread distribution method. Efficient for medium densities (up to 10 kW/rack)
Overhead	Cold air is distributed through ceiling ducts and directed toward cold aisles	Compatible with flat floors	Necessary when there is no raised floor. Requires careful duct design to avoid hot spots
InRow	Cooling units installed between racks, supplying cold air at very short distance from equipment	Compatible with both	High densities (> 10 kW/rack). Supplement to the perimeter system when density grows

Rack Density and Its Relationship to the Cooling System

Rack density is the parameter that has evolved most in recent years and the one that puts the most pressure on traditional cooling systems. The rise of high-performance computing, AI, and machine learning has taken average rack density from the 5–6 kW/rack of a decade ago to values of 20, 30, or even 100 kW/rack in specialized installations.

Classification by Density and Associated Cooling Technology

Density	kW/rack	Typical Equipment Type	Recommended Cooling Technology
Low Density	Up to 5 kW	1U servers, Telco, networking	Perimeter CRAC/ CRAH with standard raised floor
Medium Density	5 – 10 kW	Enterprise servers, storage	CRAC/CRAH with aisle containment
High Density	10 – 20 kW	HPC, high-speed storage	InRow + containment, or water-cooled rear door
Very High Density	> 20 kW	Blade servers, GPU for AI, HPC	Direct Liquid Cooling (DLC), immersion

The Mixed-Density Rack Problem

A room with racks of very different densities (some at 3 kW, others at 15 kW in the same row) is one of the most difficult scenarios for the cooling system to manage. The system is sized for the worst case, but air distribution cannot adapt dynamically. The solution is to group racks by density into dedicated zones with specific cooling systems for each zone.

PUE as a Cooling Efficiency Indicator

PUE (Power Usage Effectiveness) is the standard energy efficiency indicator for a data center. It is defined as the total energy consumed by the facility divided by the energy consumed by IT equipment. A PUE of 1.0 means all energy goes to IT equipment (impossible in practice); a PUE of 2.0 means that for every kWh the servers consume, another kWh is consumed by the infrastructure.

The cooling system is the main driver of PUE in most installations. The strategies with the greatest impact on reducing it are:

- Raise air supply temperature to the maximum of the ASHRAE recommended range (27°C at equipment inlet).
- Implement free cooling to reduce or eliminate compressor use during hours of favorable outdoor temperature.
- Implement aisle containment to eliminate air mixing and reduce required airflow.
- Remove missing blanking panels from racks to prevent internal recirculation.
- Audit the raised floor system to identify and seal air leaks.

PUE Level	Rating	Typical Characteristic
< 1,2	Excellent	Free cooling, containment, high density. Hyperscalers
1,2 – 1,5	Good	Aisle containment, elevated supply temperature
1,5 – 2,0	Needs Improvement	No containment, low supply temperature, no free cooling
> 2,0	Poor	No air management, comfort A/C, severe oversizing

Conclusion: Cooling as an Operational Advantage

A data center cooling system is not just an auxiliary service that keeps temperature within range. It is a system that determines availability, energy efficiency, operating cost, and the ability to scale compute density. Managing it rigorously is, in the most literal sense, a competitive advantage.

Professionals who understand psychrometrics can anticipate condensation risks that others do not see. Those who know the differences between technologies can correctly size the system from the design stage. Those who implement aisle containment and optimize supply temperature transform that understanding into savings on the electricity bill every month.

The Five Principles of Efficient Cooling

1. The reference temperature is the IT equipment inlet, not the room temperature. Measure where it matters.
2. Comfort A/C is not an alternative to precision A/C: it is a documented operational risk.
3. Raise the supply temperature to the limit of the ASHRAE recommended range. Every degree counts.
4. Implement aisle containment before adding more cooling units. Airflow efficiency has a better ROI than adding cooling capacity.
5. Classify racks by density and assign specific cooling technology for each zone. A single system for mixed densities is always inefficient.