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Research Article

Desiccant Dehumidification in Large Data Centers: A Quantitative and Strategic Roadmap for Sustainable Environmental Control

[1]Vrushank Mistry, [2]Hitesh Vora, [3]Dhruv Shah
[1]*BAS Project Manager, Frank M. Booth, CA mvrushank1@gmail.com*
[2]*Controls Deployment Engineer, Amazon Data Services Inc, Herndon, VA, USA , erhiteshvora@gmail.com*
[3]*Field Engineer SLS Controls, NY, USA dhruv.1005.shah@gmail.com*

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ABSTRACT

In the era of exponential data growth, modern data centers have evolved into energy-intensive infrastructures demanding precise environmental control. While temperature management is a well-recognized priority, relative humidity control is equally critical, particularly in high-density IT environments. Desiccant dehumidification offers a compelling alternative to traditional refrigeration-based methods, especially in cooler environments or when pursuing free cooling strategies. This paper provides a detailed analysis of desiccant dehumidifiers, including operational principles, psychrometric load calculations, regeneration energy models, and their integration within data center design. Through case studies, design models, and energy efficiency analysis, we propose a comprehensive roadmap for integrating desiccant dehumidification as a resilient and sustainable environmental control strategy.

Keywords: infrastructures, environmental control, dehumidification, Residual Dense Network, sustainable.

1. INTRODUCTION

1.1 Background & Relevance

Global digitization has spurred a surge in hyperscale and colocation data centers, with power densities reaching as high as 15–25 kW per rack. Such environments require not only cooling but also tight control of air moisture content to mitigate risks like electrostatic discharge (ESD) or component corrosion.

According to ASHRAE, the optimal RH range for data centers is typically 40–60%, with newer Tier III/IV facilities adopting narrower bands such as 45–55%.

Traditional cooling systems often incorporate refrigerant-based dehumidifiers, which condense water by cooling air below its dew point. However, this method becomes inefficient at low temperatures or when deep dehumidification is required. In contrast, desiccant systems remove water via adsorption, decoupling moisture removal from temperature control.

1.2 Scope and Objectives

This research aims to:

- Explore the operational principles of desiccant dehumidifiers.
- Present psychrometric and thermodynamic calculations for system sizing.
- Evaluate the integration of desiccants with air handling units (AHUs), chilled water loops, and economizer cycles.
- Propose strategies for reducing reactivation energy via heat recovery or AI-optimized control.

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- Provide real-world scenarios with performance metrics and return-on-investment (ROI) models.

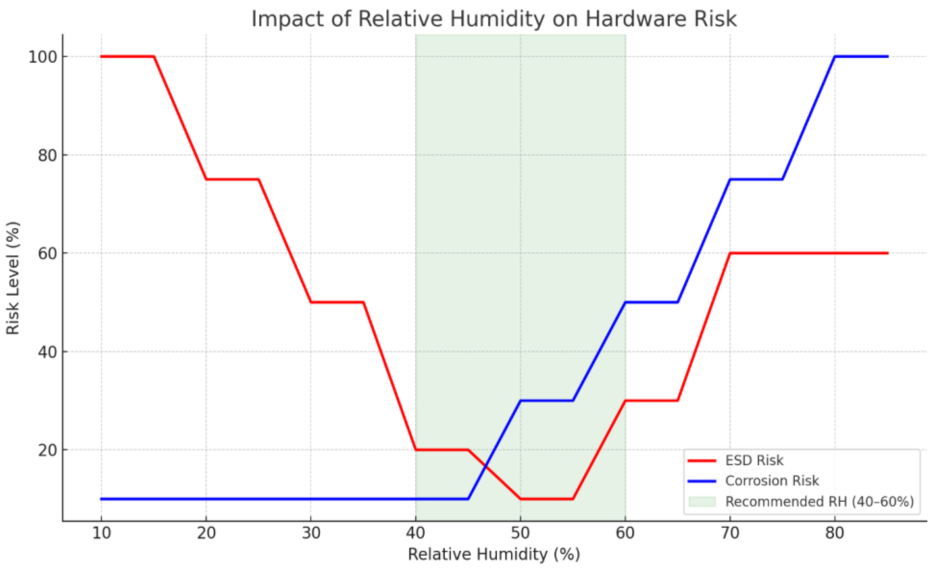
2. HUMIDITY CONTROL IN DATA CENTERS

2.1 Why Humidity Control Matters

Condition	Consequence
Too Dry (<25% RH)	Increased ESD risk, damaging CPUs, memory, and NICs
Too Humid (>70% RH)	Condensation risk, corrosion of solder joints, circuit boards, and connectors
Fluctuating RH	Mechanical stress, fogging in fiber optics, false alarms in monitoring systems

Figure 1: *Impact of Relative Humidity on Hardware Reliability*

Source: Auther's own Processing.



Note: Chart illustrating risk thresholds for condensation and ESD across different RH bands.

This chart visualizes the relative risk levels of Electrostatic Discharge (ESD) and Corrosion/Condensation as a function of relative humidity (RH).

- Red Line: ESD risk is highest below 30% RH, especially under 20%.
- Blue Line: Corrosion risk escalates significantly above 60% RH.
- The green shaded band (40–60%) represents the recommended RH range by ASHRAE for optimal IT equipment reliability.

3. DESICCANT DEHUMIDIFIER FUNDAMENTALS

3.1 System Overview

Desiccant dehumidifiers operate by drawing moist air over a rotating wheel embedded with a hygroscopic material (usually silica gel). Moisture binds to the desiccant and is then released during the reactivation cycle using a heated airstream.

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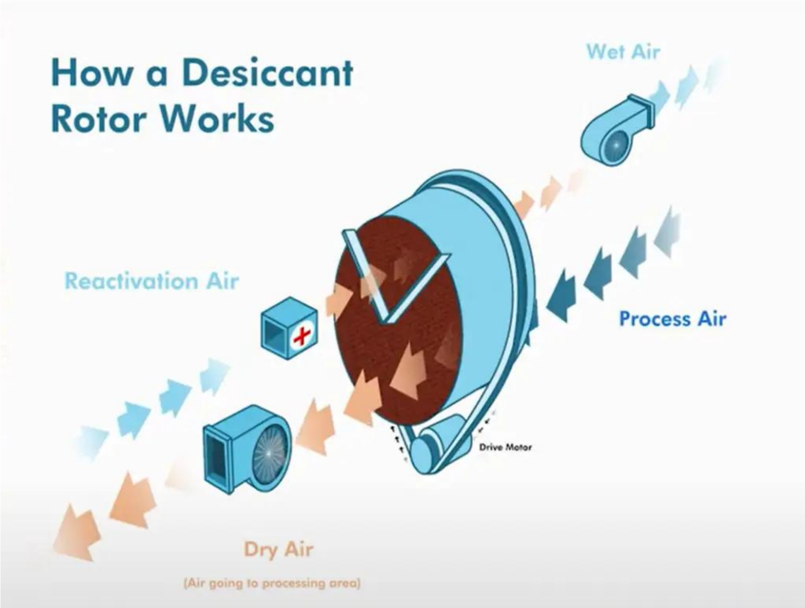
Figure 2: *Desiccant Dehumidification Process Flow*

Source: https://www.jalonzeolite.com/how-does-a-desiccant-dehumidifier-work/



Process air is dehumidified, while reactivation air carries moisture away via thermal reactivation.

1. Process Air Inlet

- Source: Typically outdoor air or recirculated return air from the data center.
- Condition: Warm and humid.
- Objective: Remove excess moisture to achieve target RH for the IT environment.

2. Desiccant Rotor (Wheel)

- The core component of the system.
- A slowly rotating wheel coated with a hygroscopic material (e.g., silica gel or lithium chloride).
- As humid process air passes over the rotor, moisture is adsorbed onto the desiccant surface.
- The air leaves drier, but typically warmer, due to the exothermic nature of adsorption.

3. Post-Cooling Coil (Optional)

- Because desiccant drying raises air temperature, this coil is used to cool the dry air before it enters the data center.
- Maintains thermal comfort and protects equipment.

4. Reactivation Air Stream

- A separate airstream, often pulled from return air or ambient environment.
- Heated to 180–250°F (typically via electric, gas, or waste heat).
- Directed through the rotor in the opposite segment, where it desorbs the adsorbed moisture.

5. Moisture-Laden Exhaust

- The reactivation airstream now carries the removed water vapor.

- This stream is vented outside to prevent reintroduction of moisture into the building.

Continuous Operation

- **The desiccant wheel rotates slowly (~6–20 RPM), continuously cycling between:**
  - **Moisture adsorption (process air side)**
  - **Moisture desorption (reactivation side)**

Key Benefits of This Flow:

- Works well at lower temperatures where conventional cooling coils lose efficiency.
- Decouples humidity control from temperature control, offering greater flexibility.
- Enables integration with free cooling or waste heat recovery systems.

3.2 Core Components

Component	Function
Desiccant Rotor	Adsorbs moisture from process air
Reactivation Heater	Supplies thermal energy (gas, electric, or waste)
Fans & Ducting	Drive airflow and segregate process/react streams
Post-Cooling Coil	Reduces air temperature post-dehumidification

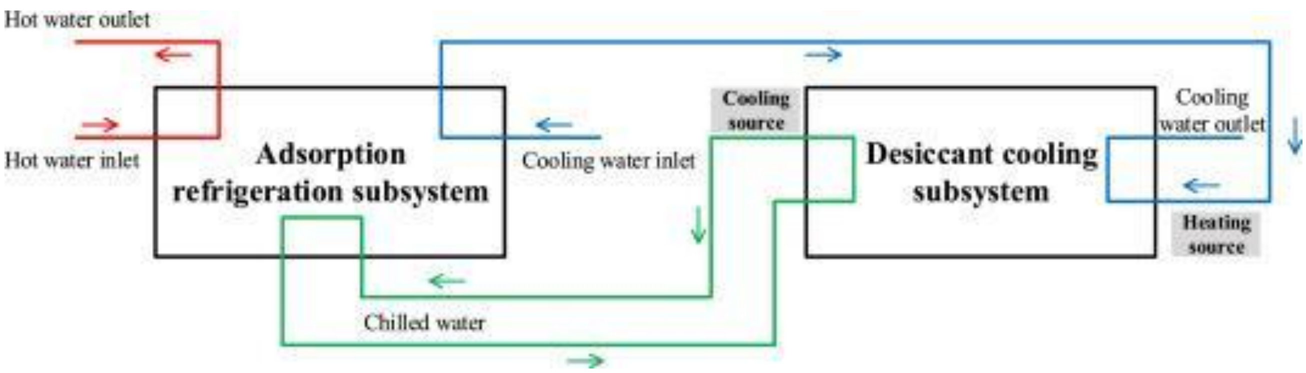
4. DESICCANT INTEGRATION IN DATA CENTERS

4.1 Integration Architectures

- **Standalone Desiccant Units**
  Installed upstream of cooling systems to handle outside air before it enters the AHU.
- **Hybrid AHU Integration**
  Combines desiccant and refrigerant coils to achieve both RH and temperature targets efficiently.
- **Free Cooling-Enabled**
  When using economizers, desiccants ensure RH remains within safe limits despite varying ambient conditions.

Figure 3: *Hybrid Integration of Desiccant and Chiller Loops*

Source : https://doi.org/10.1016/j.rser.2022.112890



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5. MOISTURE LOAD CALCULATIONS: A STEP-BY-STEP EXAMPLE

Here, we merge real-world design considerations with fundamental psychrometrics to illustrate sizing.

Psychrometric Variables

- **Dry-Bulb Temperature (Tdb):** Air temperature measured by a standard sensor (°F or °C).
- **Relative Humidity (RH):** The ratio of the partial pressure of water vapor in the air to the saturation pressure at that temperature (dimensionless, often in %).
- **Humidity Ratio (W):** The mass of water vapor per mass of dry air.

W = 0.622 * (p_v / (p_atm - p_v)) where p_v is the partial pressure of water vapor, and p_atm is atmospheric pressure.

- Enthalpy (h): Total heat content of moist air, expressed per unit mass of dry air.

h = h_dry_air + (W * h_v) h_v is the enthalpy of vapor at the given temperature.

- Dew Point (Tdp): The temperature at which air becomes saturated (RH = 100%) at the current moisture content.

Example Airflow and Moisture Removal

- **Suppose we have:**
  - Supply Air Condition: 72 °F, 45% RH
  - Outside Air Condition: 90 °F, 80% RH
  - Volume Flow Rate (V) = 50,000 cfm
- **From psychrometric tables or software, approximate:**
  - W_OA (outside air) ≈ 0.019 lb water / lb dry air
  - W_supply (target supply) ≈ 0.008 lb water / lb dry air

5.1 Mass Flow Rate of Dry Air

Assume standard air density of approximately 0.075 lb dry air / ft³. Convert cfm to lb/hr:

m_air = V * 60 * rho_air

m_air = 50,000 cfm * 60 (min/hr) * 0.075 (lb/ft³)

m_air ≈ 225,000 lb dry air / hr

5.2 Moisture Removed by the Desiccant

The desiccant must remove the difference in water vapor between outside air and supply: m_H2O = m_air * (W_OA - W_supply)

m_H2O = 225,000 lb/hr * (0.019 - 0.008)

m_H2O ≈ 2,475 lb water / hrRegeneration (Reactivation) Energy

- Desiccant rotors require a hot air stream to drive off absorbed moisture. Assume:
  - Reactivation Airflow is half the main process flow: ~112,500 lb/hr
  - Heating the airstream from 80 °F to 220 °F
  - Latent heat of vaporization for water near 212 °F: ~1,050 Btu/lb

5.3 Reactivation Heat Calculation

Q_react = [m_air,react * c_p_air * (T_react - T_inlet)]

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+ [m_H2O_desiccant * h_fg]

where:

- m_air,react: mass flow rate of reactivation air (lb/hr)
- c_p_air: specific heat of air (about 0.24 Btu/lb-°F)
- T_react: final reactivation air temperature (°F)
- T_inlet: initial reactivation air temperature (°F)
- m_H2O_desiccant: amount of water to be driven off in lb/hr
- h_fg: latent heat of vaporization (Btu/lb)

5.4 Example Numbersm_air,react ≈ 112,500 lb/hr

c_p_air ≈ 0.24 Btu/lb-°F

T_react = 220 °F

T_inlet = 80 °F

m_H2O_desiccant = 2,475 lb/hr

h_fg ≈ 1,050 Btu/lb

Q_react ≈ [112,500 * 0.24 * (220 - 80)] + [2,475 * 1,050]

Sensible heating (first bracket):

112,500 * 0.24 * 140 ≈ 3,780,000 Btu/hr

Latent heat (second bracket):

2,475 lb/hr * 1,050 Btu/lb ≈ 2,598,750 Btu/hr

Total:

3,780,000 + 2,598,750 ≈ 6.38 x 10^6 Btu/hr3.3

Convert Btu/hr to kW
Recall 1 kW ≈ 3,412 Btu/hr:

6.38 x 10^6 Btu/hr / 3,412 (Btu/hr per kW)

≈ 1,870 kW

7. ENERGY EFFICIENCY MEASURES

7.1 Waste Heat Utilization

Use server exhaust (90–120°F) or a CHP plant to preheat reactivation air.

7.2 AI-Enhanced Controls

BMS-driven analytics can modulate:

- Wheel speed
- Reactivation airflow
- Start/stop timing based on occupancy/load forecasts

7.3 Heat Exchangers

Install rotary thermal wheels to recover sensible heat before exhausting the reactivation stream.

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8. ECONOMIC AND LIFECYCLE ANALYSIS

8.1 Capital and Operating Costs

Component	Cost Range (USD)
Desiccant Wheel + Housing	$25,000 – $75,000
Reactivation Heater (Gas/Electric)	$10,000 – $30,000
Post-Cooling Coils	$5,000 – $15,000
Installation & Commissioning	$10,000 – $40,000
Controls & Integration (BMS)	$5,000 – $20,000

Total Typical Installed Cost: $50,000 – $180,000 per system (depending on airflow and capacity).

8.2 Operational Expenditures (OpEx)

Assuming:

- Energy cost: $0.10/kWh
- Reactivation energy: 1,870 kW from previous calculation
- Runtime: 8 hours/day, 300 days/year

Annual OpEx=1,870 kW×8×300×0.10= $448,800

8.3 Return on Investment (ROI)

Example:
A data center replaces 3 chilled-water coils for dehumidification with desiccant units and integrates free cooling.

- Energy savings: $160,000/year
- Reduced maintenance/downtime: $50,000/year
- Total annual benefit: $210,000
- Installation cost: $600,000

Simple Payback Period:

600,000/210,000 ≈ 2 .86 years

9. CASE STUDIES

9.1 Case 1: Hyperscale Data Center (Iceland)

- **Ambient Conditions**: Cool, humid climate
- **Approach**: Air-side economizer + desiccant dehumidification
- **Result**:
  - 75% reduction in chiller hours
  - $1.2M annual savings
  - Maintained 45% RH with minimal downtime
  - Payback in 2.5 years

9.2 Case 2: Edge Facility in Southeast Asia

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- **Ambient Conditions**: High temp + humidity
- **Challenge**: Poor refrigerant coil performance
- **Solution**: Modular desiccant units integrated with split DX system
- **Impact**:
  - 38% lower humidity excursions
  - 15% less cooling energy
  - 98.7% uptime over 12 months

10. Environmental and Sustainability Analysis

10.1 Carbon Footprint Reduction

- **Baseline**: 1 MWh of electricity = ~0.45 metric tons CO_2 (US grid average)
- **Annual desiccant system load**: ~4,000 MWh
- **Offset via Waste Heat + Free Cooling**: ~40%

Net Reduction:

$4{,}000 \times 0.45 \times 0.4 = 720$ metric tons CO_2/year

10.2 Water Use Efficiency

Unlike chilled coils requiring condensate drainage and humidifiers needing make-up water, desiccant systems:

- Require **no water supply**
- Eliminate **condensate pumps**
- Reduce **risk of microbial growth**

11. CHALLENGES AND MITIGATION STRATEGIES

Challenge	Mitigation Strategy
High reactivation energy	Waste heat recovery, thermal wheels, solar assist
Rotor maintenance	Quarterly inspections, filters on process air
Temperature spikes post-wheel	Post-cooling coil or hybrid AHU configuration
Initial CapEx	Modular installation, staggered rollout

12. MODELING AND SIMULATION

12.1 Humidity vs Energy Demand

Figure 4: *Simulated Energy Demand vs RH Setpoints*

Lower RH targets require higher reactivation energy. Optimization recommended around 45–50% RH for balance.

12.2 Annual Load Profile (with and without desiccant)

Figure 5: *Annual Cooling Load Comparison*

Free cooling and desiccant integration reduce summer peaks and annual cooling energy.

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13. FUTURE TRENDS

13.1 Smart Adaptive Control

AI-driven building management systems (BMS) can:

- Predict RH load using weather and IT load data
- Pre-activate desiccant systems
- Minimize energy spikes via real-time modulation

13.2 New Desiccant Materials

- **Metal-organic frameworks (MOFs)**: High adsorption at low humidity
- **Composite gel beads**: Reusable, lower-temperature reactivation
- **Bio-based materials**: Eco-friendly, potentially biodegradable

13.3 Integration with Liquid Cooling

Desiccant air systems may work alongside:

- Direct-to-chip liquid cooling
- Rear-door heat exchangers
  Reducing airflow demand while maintaining RH control for ambient spaces.

14. CONCLUSION

Desiccant dehumidification systems provide a sustainable, efficient, and scalable solution for large-scale data centers facing increasing cooling and environmental control demands. Their ability to operate effectively in low-temperature or high-humidity conditions makes them ideal complements to economizer-based and free cooling strategies.

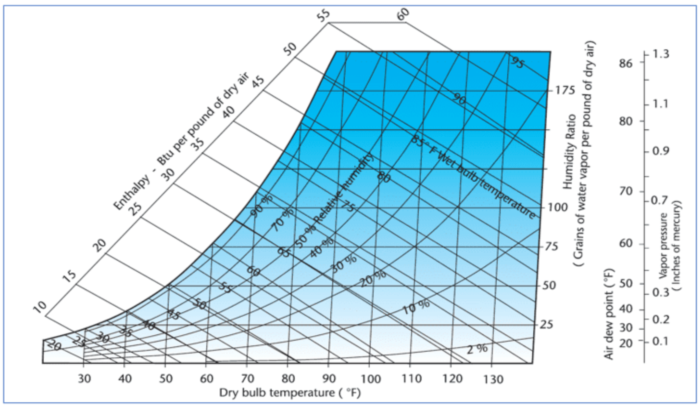
Although reactivating energy can be significant, the integration of waste heat reuse, thermal energy recovery, and intelligent control systems mitigates this challenge—often yielding favorable ROI and long-term energy savings. By ensuring robust humidity control, desiccant systems also extend hardware life, reduce maintenance, and support ESG compliance.

With emerging materials and AI-enhanced performance tuning, desiccant dehumidification will likely play a critical role in next-generation hyperscale and modular data center infrastructure.

Appendices

A. Psychrometric Chart with Key Points Labeled

Source : https://kta.com/painting-tank-interior/



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B. Calculation Tables

Parameter	Value
Process Flow Rate	50,000 CFM
Moisture Load	2,475 lb/hr
Reactivation Energy	6.38 MMBtu/hr
Cost of Operation	$448,800/year

REFERENCES

[1] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), *Thermal Guidelines for Data Processing Environments*, 4th ed., ASHRAE TC 9.9, Atlanta, GA, 2015.
[2] J. Van Straaten, R. Mitchell, and T. L. Roper, "Desiccant cooling: a review of recent advances," *Energy*, vol. 27, no. 6, pp. 587–600, Jun. 2002, doi: 10.1016/S0360-5442(02)00114-7.
[3] R. I. Christodoulaki, E. D. Rogdakis, and I. P. Koronaki, "Optimal operation of desiccant wheel for air conditioning applications," in Proceedings of the ASME 9th Biennial Conference on Engineering Systems Design and Analysis (ESDA 2008)
doi: 10.1115/ESDA2008-59344
[4] U.S. Department of Energy (DOE), *Energy Efficiency Trends in Commercial and Data Center Buildings*, Washington, D.C., 2021. [Online]. Available: https://www.energy.gov/eere/buildings
[5] National Renewable Energy Laboratory (NREL), *Desiccant Performance Modeling Toolkit*, Golden, CO, 2022. [Online]. Available: https://www.nrel.gov/
[6] Uptime Institute, *2023 Global Data Center Survey Report*, Uptime Institute, New York, 2023. [Online]. Available: https://uptimeinstitute.com
[7] Bry-Air, *Desiccant Dehumidification Technical Handbook*, 2020. [White Paper]. Available: https://www.bry-air.com/
[8] Munters Corporation, *Desiccant Rotor Technology: Performance and Applications*, Munters, Amesbury, MA, 2019.