International Institute of Refrigeration

# Dehumidification in Air Conditioning

62nd TECHNICAL BRIEF ON REFRIGERATION TECHNOLOGIES

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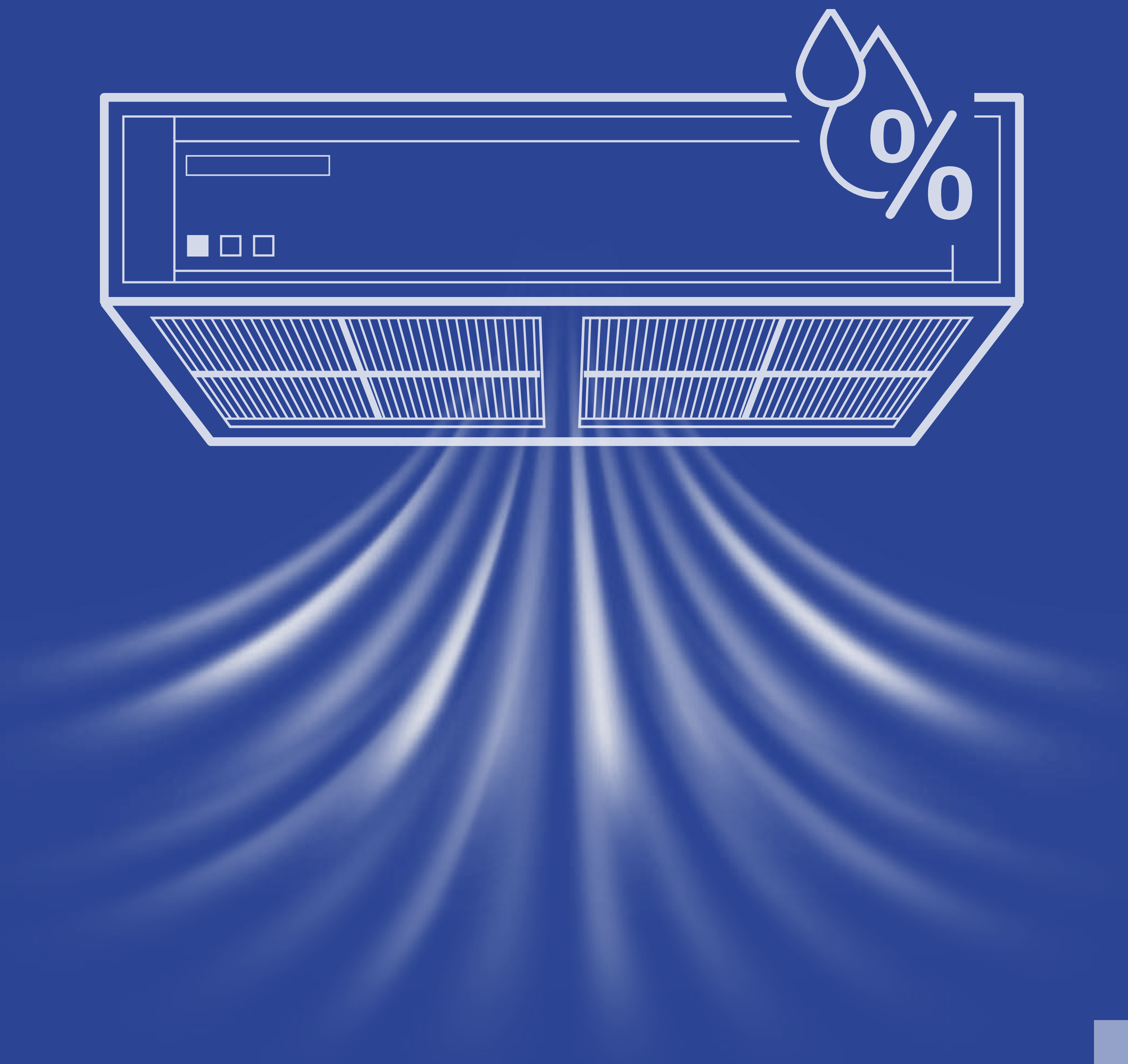

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# Summary

**This technical brief reviews typical air-conditioning processes involving dehumidification and major air dehumidification technologies. Condensation dehumidification, liquid desiccant systems, solid desiccant systems, and typical emerging approaches are analysed in detail. For each category, the fundamental dehumidification principles, application scenarios, typical system configurations, representative materials or working media, and recent advances in performance enhancement are summarised.**

A comparative assessment is conducted in terms of dehumidification capability, energy performance, technological maturity, and engineering applicability, providing guidance in order to identify suitable dehumidification technologies under different operating conditions, humidity-control requirements, and application scenarios.

Overall, this brief offers a structured framework for understanding the characteristics, development status, and application suitability of various air dehumidification technologies.

# 1 / Introduction

**The global demand for air conditioning (AC) has surged rapidly, driven by climate change, urbanisation, and rising living standards, particularly in hot and humid regions such as Southeast Asia, Africa, and Central America. While AC systems enhance indoor thermal comfort, their escalating energy consumption has become a significant driver of global electricity demand and associated greenhouse gas emissions. In hot and humid climates, HVAC systems can account for over 50% of a building's total energy consumption[1], with more than half of this load attributed to latent heat removal (dehumidification).**
**Consequently, developing high-efficiency dehumidification technologies represents a critical strategy for improving the overall energy performance of comfort cooling systems.**

Beyond comfort applications, numerous industrial processes necessitate strict humidity control to ensure product quality and process stability. Sectors such as electronics manufacturing, lithium battery production, pharmaceutical manufacturing, and optical fabrication often rely on low-humidity environments. These processes typically demand deep dehumidification and continuous operation, leading to substantial energy consumption. For industrial facilities with high dehumidification loads, studies indicate that optimising dehumidification technologies can yield system energy savings of 20–30% or more[2]. This underscores the urgent need to develop advanced, energy-efficient dehumidification solutions.

This technical brief evaluates condensation, desiccant, and emerging dehumidification technologies, analysing their efficiency, market penetration, applicability, and ability to meet diverse sectoral needs. By comparing the operational characteristics and practical applications of these technologies, this report aims to provide a comprehensive reference for selecting optimal dehumidification strategies across various scenarios.

# 2 / Typical air-conditioning process with dehumidification

Precise control of both temperature and humidity is fundamental to effective indoor environmental regulation. Based on the sequence and coupling of these thermodynamic treatments, air handling processes are generally categorised into two distinct approaches: simultaneous handling or independent handling of temperature and humidity.

## 2.1 Simultaneous handling of temperature and humidity

In conventional AC systems, temperature and humidity are regulated simultaneously within a single process. As illustrated in **Figure 1 (a)**, mixed outdoor and return air undergoes filtration, cooling and dehumidification, and often reheating, before supply. Moisture is removed by cooling air below its dew point [1]; its reheating then restores the supply temperature. On the psychrometric chart shown in **Figure 1 (b)**, this process follows a trajectory where the air state first moves along the apparatus dew point line to reduce humidity, followed by a sensible heating process along a constant humidity ratio line. While this integrated approach is conceptually simple, technologically mature, and widely deployed in offices, shopping malls, and hotels, it incurs an energy "reheat penalty" and challenges the system's ability to achieve deep dehumidification (typically limited to >2–4 g/kg dry air).

## 2.2 Independent handling of temperature and humidity

Independent temperature and humidity control systems, also referred to as separate sensible and latent cooling systems, dissociates the dehumidification of air from the sensible cooling of air. **Figure 2 (a)** illustrates a typical dedicated outdoor air unit which uses two parallel recirculating units to handle sensible cooling and latent cooling. Outdoor air follows a strong dehumidification path, whereas return air cools along a constant humidity ratio line before mixing. The two airstreams merge downstream to form the final supply air.

The dehumidification unit can employ various dehumidification technologies, including condensation dehumidification, liquid desiccant dehumidification, or solid desiccant dehumidification. This independent temperature and humidity control system removes the need for reheating to achieve precise temperature and humidity control, thereby improving energy efficiency. Additionally, if the dehumidification unit uses liquid desiccant dehumidification or solid desiccant dehumidification, the achievable humidity ratio can be further lowered. **Figure 2 (b)** shows the psychrometric chart of temperature and humidity independent handling systems when using condensation dehumidification.

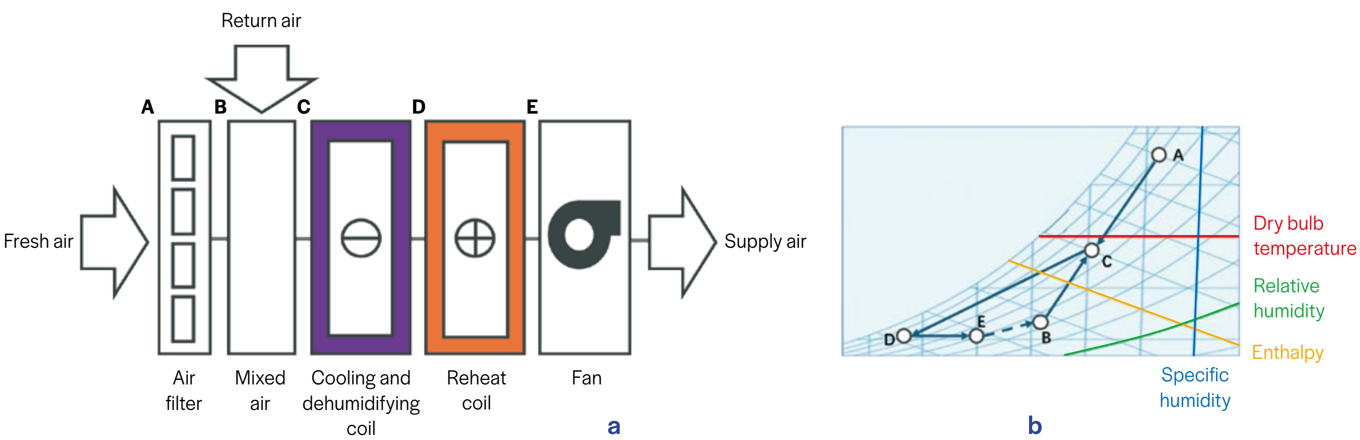
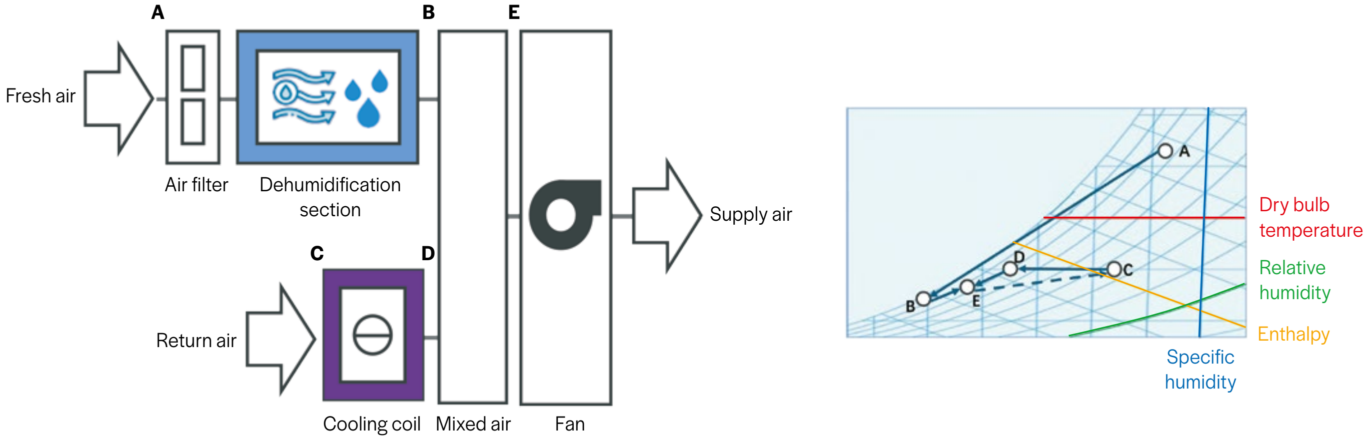



**Figure 1** | Typical temperature and humidity simultaneous handling systems. **(a)** System flow chart. **(b)** Psychrometric chart.

1. The dew point is the temperature at which the air must be cooled at a constant absolute humidity and pressure so that the relative humidity rises to 100%.




a

b

**Figure 2** | Typical temperature and humidity independent handling systems. **(a)** System flow chart. **(b)** Psychrometric chart.

# 3 / Air dehumidification technologies

Different dehumidification technologies can be incorporated into the air handling processes to facilitate steam removal. Currently, the in-use and potential dehumidification technologies include condensation dehumidification, desiccant dehumidification, and membrane dehumidification.

## 3.1 Condensation dehumidification

### 3.1.1 Principle

Condensation dehumidification removes moisture by cooling air below its local dew point. As illustrated in Figure 3, moist air passes over a cold surface (evaporator); when the adjacent air temperature drops below the dew point, water vapour condenses into liquid, reducing absolute humidity. The condensate is then drained. This process can be driven by various chilled media, including chilled water, vapour compression systems, and thermoelectric modules.

### 3.1.2 Typical condensation dehumidifier

**Vapour compression refrigeration dehumidifier**

Direct expansion vapour compression refrigeration (VCR) dehumidifiers are widely used to cool air (Figure 4). Based on airflow configuration and outlet temperature, they are categorised into two types:

- Cooling Dehumidifiers: The process air passes solely over the evaporator, resulting in simultaneous cooling and dehumidification. This yields the lowest outlet temperatures, typically 11–15°C with 80–100% relative humidity (RH)[3].
- Temperature-Adjustable Dehumidifiers: Air cooled by the evaporator passes partially or fully through the condenser, absorbing condensation heat to control outlet temperature. When outlet and inlet dry-bulb temperatures match, the unit functions as a thermostatic dehumidifier.

VCR dehumidifiers exhibit high energy efficiency, with electrical coefficients of performance ($COP_e$, ratio of the cooling capacity to the consumed electrical energy) ranging from 2.5 to 4.0[4]. While prevalent in industrial, commercial, and residential buildings, they are less suitable for low-temperature applications due to frost formation risks around the coil[5].

**Thermoelectric refrigeration dehumidifier**

Thermoelectric refrigeration (TER) dehumidifiers use the solid-state Peltier effect. When an electric current is applied to a thermoelectric module, one side cools down while the

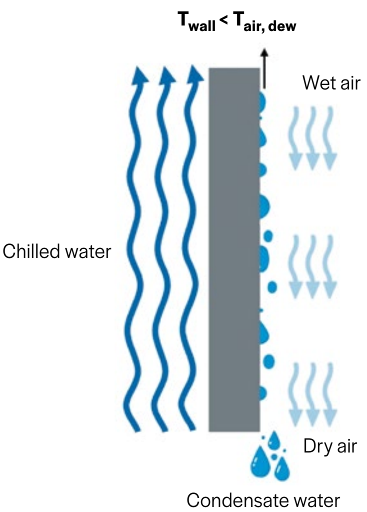



**Figure 3** | Principle of condensation dehumidification.

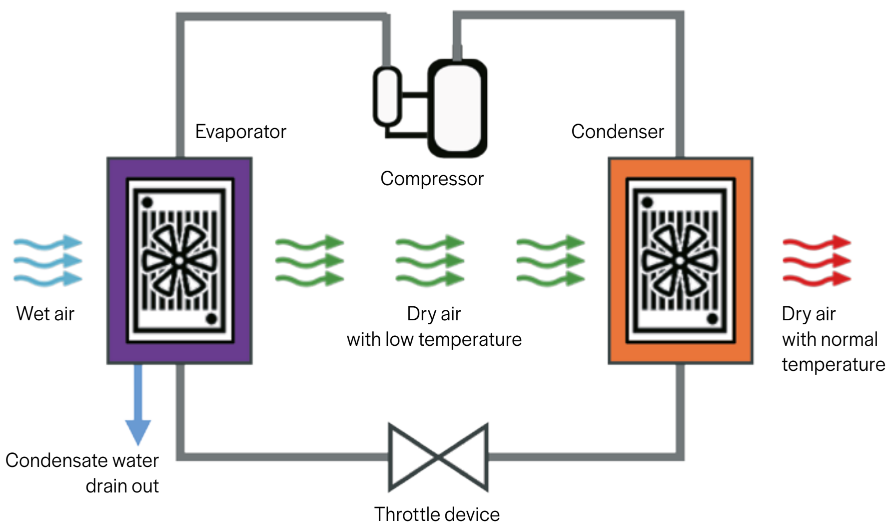



**Figure 4** | Schematic diagram of a vapour compression refrigeration dehumidifier.

other heats up. Moist air is passed over the cold side, causing moisture to condense, while the heat sinks and fans dissipate heat from the hot side (**Figure 5**).

Although TER systems have lower electrical efficiency ($COP_e$ = 0.4~0.7) compared to VCR units[6], their compactness, portability, and silent operation make them ideal for small spaces such as closets, offices, and vehicles. They are also well-suited for moderate humidity control in sensitive environments such as libraries and laboratories[5]. Future advancements depend on material innovations (e.g., high figure of merit – ZT value – $Bi_2Te_3/Sb_2Te_3$ superlattices[7]) and design optimisations, including enhanced air-thermoelectric module (TEM) contact, frost reduction via pulsating power, and improved heat sink geometries[8].

## 3.2 Liquid desiccant dehumidification

### 3.2.1 Principle

Liquid desiccant dehumidification removes moisture via direct contact mass transfer between humid air and a hygroscopic solution (e.g. lithium chloride, LiCl). Unlike VCR systems that rely on cooling air below its dew point, this technology handles latent loads by harnessing the vapour pressure difference between the air and the desiccant.

A typical system comprises a liquid desiccant total heat exchanger coupled with a regeneration unit (**Figure 6 (a)**). Within the exchanger, a solution circulates between two direct-contact heat exchangers (DCHE), facilitating simultaneous heat and moisture transfer. The absorption

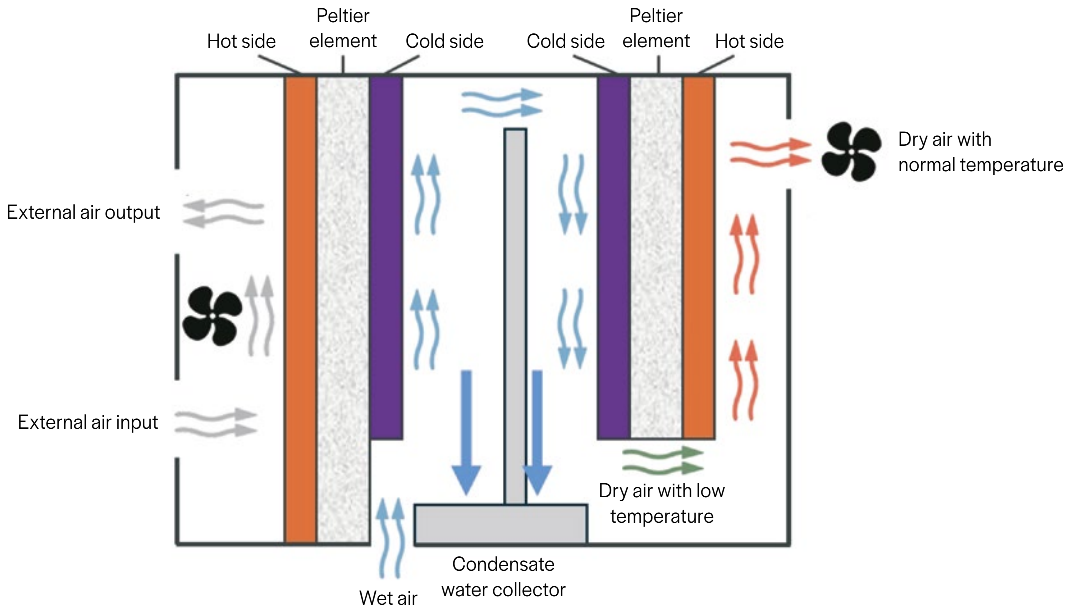



**Figure 5** | Schematic diagram of a thermoelectric refrigeration dehumidifier.

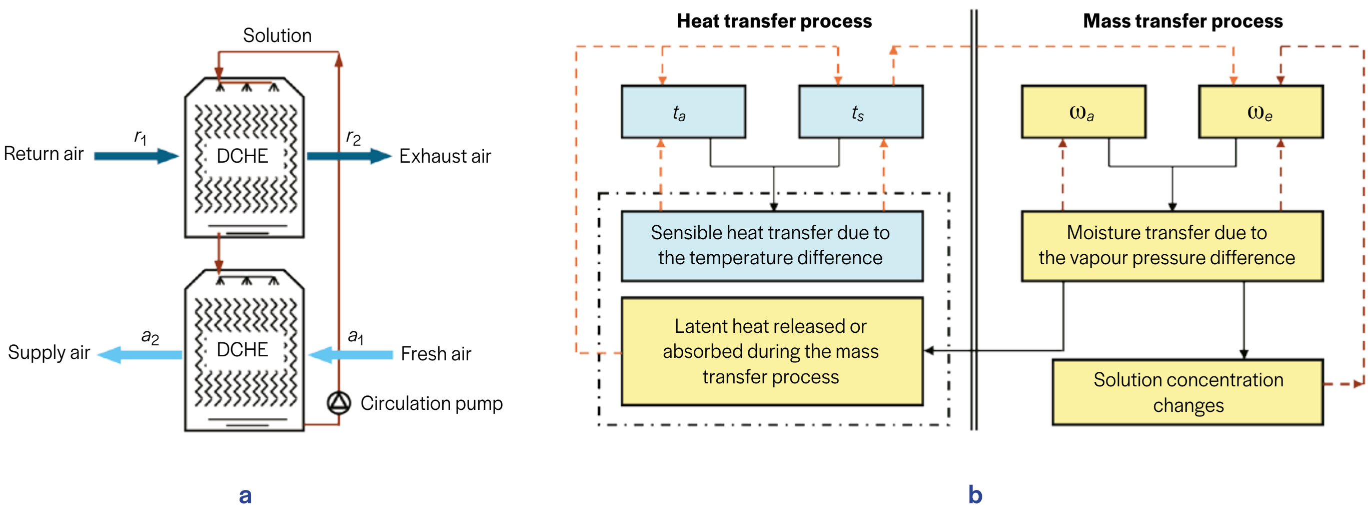



**Figure 6** | System configuration of liquid desiccant total heat exchanger. **(a)** Schematic of the liquid desiccant heat exchanger. **(b)** Heat and mass transfer processes.

process is governed by the air temperature ($t_a$) and humidity ratio ($\omega_a$), alongside the solution temperature ($t_s$) and its equilibrium humidity ratio ($\omega_a$) converted from the vapour partial pressure of the desiccant solution (**Figure 6 (b)**). Moisture transfers from air to solution when $\omega_a > \omega_e$, as occurs in DCHE handling fresh air. Conversely, when $\omega_a < \omega_e$ (in DCHE handling return air), moisture transfers from solution to air. While the fundamental heat and mass transfer mechanisms remain consistent across seasons, the direction and magnitude vary with temperature and humidity gradients. This bidirectional capability enables the recovery of both sensible and latent energy from exhaust air, significantly improving overall energy efficiency[9].

Key advantages include high energy efficiency, pollutant removal[10], and improved indoor air quality. When integrated into temperature–humidity independent control systems, liquid desiccant technology offers a wider regulation range and lower outlet humidity, making it ideal for stringent environments like hospitals and laboratories. However, common desiccants (e.g. aqueous LiCl, LiBr, $CaCl_2$) pose corrosion risks to metallic components, necessitating careful material selection in system design.

### 3.2.2 Typical liquid desiccant dehumidifier

Liquid desiccant systems can be configured as packed towers, internally cooled units, multi-stage systems, or hybrids coupled with thermal sources. Among these, the heat pump-driven liquid desiccant fresh air handling unit represents a widely studied and practical configuration, as shown in **Figure 7**.

In this system, diluted solution from the absorber is regenerated using waste heat from the heat pump's condenser. The regenerated (concentrated) solution is then cooled and returned to the dehumidification module, forming a closed loop. This strategy uses low-grade thermal energy for continuous operation, markedly enhancing efficiency. Reported performance indicates an energy efficiency ratio (EER), calculated as the ratio between the cooling or heating capacity delivered to the fresh air and the compressor's power consumption, of 6.3 to 7.3 during the summer and 4.7 to 5.0 during the winter[11].

Field applications in an office building located in Shenzhen, China, demonstrated stable performance under independent temperature and humidity control[12]. In summer, supply air temperature was maintained at 20.6–21.6°C with an absolute humidity of 11 g/kg at an airflow rate of 3,950 $m^3$/h. In winter, supply air temperature ranged from 21 to 23°C with an absolute humidity of 6 g/kg at an airflow rate of 2,935 $m^3$/h. These results confirm the system's ability to precisely regulate humidity and ensure high energy efficiency in practical operations.

### 3.2.3 Recent progress in performance optimisation

In conventional adiabatic dehumidifiers, moisture absorption releases latent heat, raising the solution temperature and vapour pressure. This reduces the vapour pressure difference, the driving force for mass transfer, thereby limiting dehumidification effectiveness.

To address this issue, internally cooled liquid desiccant dehumidifiers have been developed. These systems incorporate independent cooling channels inside the absorber to remove absorption heat[13]. By suppressing the solution temperature rise, internal cooling maintains a lower vapour pressure, thus sustaining a stronger driving potential. This enhances moisture removal capacity and operational stability, particularly under high-humidity conditions.

Beyond structural improvements, performance is optimised through operational parameter regulation. In temperature–humidity independent systems, capacity is primarily controlled by adjusting airflow rates and dehumidification/regeneration temperatures. Additional factors, such as solution concentration and wheel rotation speed (in rotary systems), also significantly influence efficiency. Effective monitoring relies on key indicators: supply air temperature, humidity ratio (or dew point),

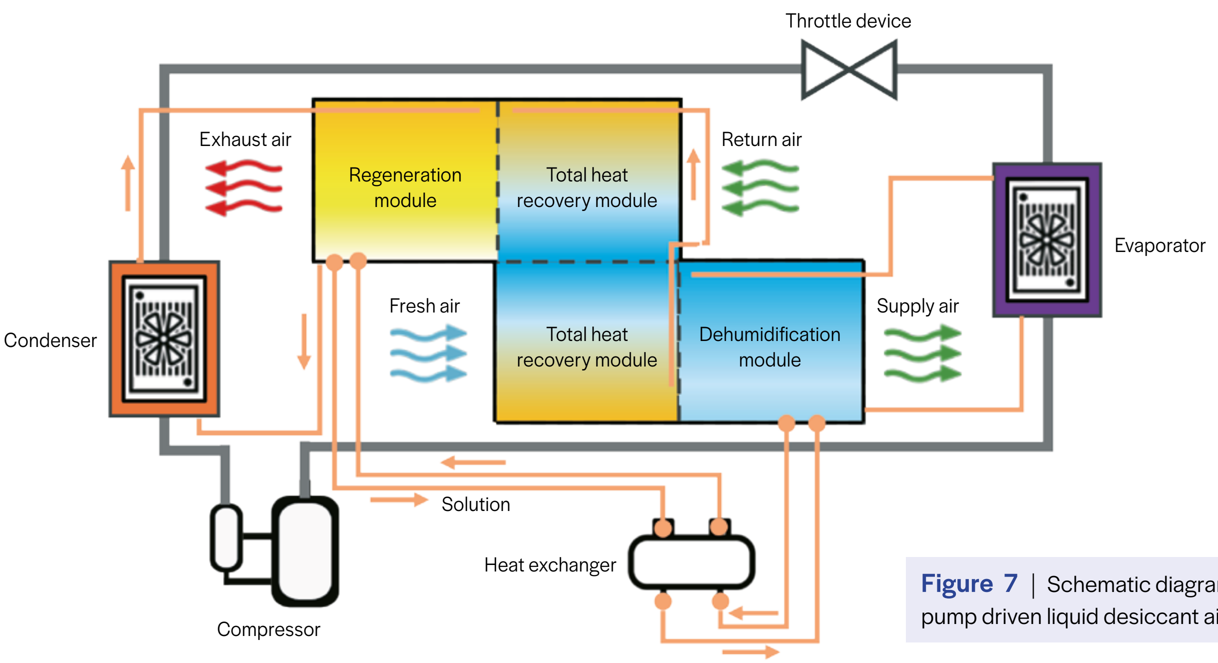



**Figure 7** | Schematic diagram of a heat pump driven liquid desiccant air processor.

regeneration temperature, and solution properties. While conventional sensors offer accuracies of ±0.1°C and ±5% RH, deep dehumidification applications often employ dew point hygrometers (±0.1°C accuracy) to ensure precise control.

Collectively, advancements in absorber design and operational strategies have expanded the feasible operating range of liquid desiccant systems, enhancing their suitability for high-performance humidity control applications.

## 3.3 Solid desiccant dehumidification

### 3.3.1 Principle

Solid desiccant dehumidification is driven by the water vapour pressure gradient between process air and the desiccant surface, operating via physical adsorption or chemical absorption[14].

- Physical Adsorption: Utilises porous materials (e.g. silica gel, molecular sieves) to capture moisture via van der Waals forces. Transport kinetics follow a multi-scale diffusion framework (molecular, Knudsen, and surface diffusion), often culminating in capillary condensation at high relative humidity.
- Chemical Absorption: Involves localised reactions where inorganic salts form crystalline hydrates upon contacting water vapour.

Characterised by mechanical simplicity and the absence of liquid carryover, these systems excel in industrial deep dehumidification, particularly when integrated with heat pumps or renewable energy sources for thermal regeneration. Their non-toxic nature, modularity, and low maintenance requirements make them ideal for applications demanding precise, ultra-low humidity control. Typical sectors include pharmaceuticals, electronics, food processing, and the preservation of sensitive materials (e.g. books, tobacco, grain) in warehouses, laboratories, hospitals, and museums[15].

### 3.3.2 Typical solid desiccant dehumidifier

Solid desiccant dehumidification technologies can be realised in several system forms, including fixed-bed adsorption systems, desiccant wheels, and desiccant-coated heat exchangers. Despite differences in structure and operation mode, these systems generally rely on the adsorption of water vapour by solid hygroscopic materials followed by thermal regeneration. Among these approaches, the desiccant wheel system is one of the most widely applied configurations in AC and industrial dehumidification.

The system employs a revolving honeycomb rotor coated with hygroscopic materials (e.g. silica gel, zeolite, composite salts, or Metal–Organic Frameworks — MOFs), divided into process and regeneration zones. In the process zone, humid air passes through the rotating honeycomb rotor coated with desiccant material, where moisture is adsorbed and dry air is delivered. As the wheel rotates into the regeneration zone, heated air removes the adsorbed moisture, restoring the sorbent for the next cycle. Continuous rotation ensures steady and uninterrupted operation[16] (see Figure 8).

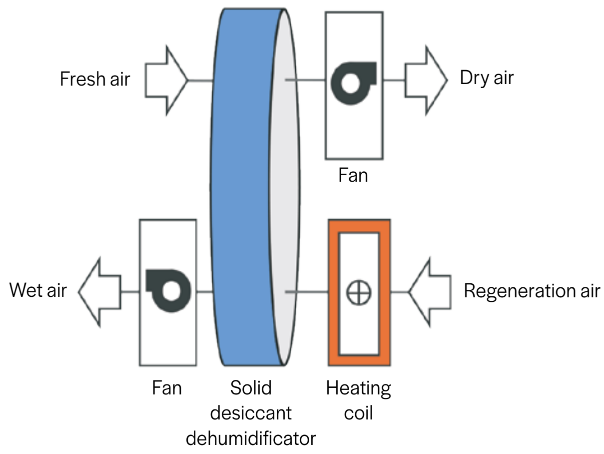



**Figure 8** | Schematic diagram of desiccant wheel dehumidifier.

Desiccant wheels achieve deep dehumidification with dew points typically below 0°C, reaching as low as **–70°C** in advanced designs[15]. Performance metrics include:

- Thermal COP ($COP_t$, ratio of the cooling capacity to the consumed regeneration heat): Ranges from 0.5 to 0.6 for single-stage systems to 0.72 for two-stage configurations[17].
- Electrical COP ($COP_e$): When integrated with a heat pump, $COP_e$ reaches 5.5 to 5.9[18].

System performance is governed by operating parameters (regeneration temperature, rotor speed, airflow), structural factors (coating thickness, channel geometry, area ratio), and material properties (adsorbent type, pore structure). Monitoring relies on capacitive, resistive, or chilled-mirror sensors to ensure precise humidity control.

### 3.3.3 Recent progress in materials and system optimisation

Research focuses on enhancing adsorbent capacity and optimising heat–mass transfer within the rotor:

- Material Innovation: Conventional silica gel and zeolites offer stability, but they have limited working capacity and high regeneration temperatures. Composite adsorbents (hygroscopic salts embedded in porous matrices) improve water uptake and lower regeneration thresholds, though salt corrosion and deliquescence remain challenges[19], [20]. MOFs represent a promising alternative, featuring tunable pores and stepwise adsorption. Their sharp uptake characteristics enable efficient operation with low-grade heat (40 to 60°C) [21], [22].
- Structural Optimisation: Advances in coating techniques, channel geometry refinement, and multi-sector rotor configurations have significantly enhanced heat–mass transfer coupling and volumetric moisture removal[23].

These combined advancements in novel materials and structural design are driving the development of next-generation solid desiccant systems that are more compact, energy-efficient, and capable of using low-grade thermal energy.

## 3.4 Other emerging dehumidification technologies

Beyond conventional methods, emerging technologies, such as membrane-based, pressure swing adsorption (PSA), and electrochemical and phase change dehumidification offer distinct advantages, including compact structures, low regeneration temperatures, and novel driving mechanisms. Among these, electrolyte membrane and hollow-fibre membrane (HFM) dehumidification have garnered significant research interest due to their unique operating principles and promising performance.

### 3.4.1 Electrolyte membrane dehumidification

Electrolyte membrane dehumidification addresses the thermal inertia and complexity of traditional systems by using electrochemical reactions for direct moisture removal. The core component is a compact membrane electrode assembly (<1 cm thick) comprising gas diffusion layers (GDL), catalyst layers (CL), and a proton exchange membrane (PEM) (**Figure 9**). Under a 2–4 V DC field, moist air passes through the GDL to the anode where oxygen evolution reactions occur; generated protons ($H^+$) migrate through the PEM to form water at the cathode. This mechanism enables rapid response and fine controllability, making it ideal for precision instruments, valuables storage, and artefact preservation[24].

Recent advancements focus on optimising the catalyst's activity and microstructure to enhance efficiency. For instance, Liu *et al.*[26] developed nanofibre $IrO_2@SbSnO_x$ catalysts via coaxial electrospinning, which reduced particle aggregation and increased active site exposure. Under identical conditions (3 V DC, 20°C, 80% RH), this module achieved a dehumidification rate of 0.504 x $10^{-4}$ g/s, more than doubling the performance of commercial $IrO_2$ (0.232 x $10^{-4}$ g/s). Further improvements are being achieved through high-hygroscopic PEMs, optimised collector plate designs, and advanced coating techniques[27], [28], as illustrated by the performance variations under different operating conditions shown in **Figure 10**.

A defining advantage of this technology is its inherent electro-humidity coupling, which simplifies system control. The dehumidification rate is directly regulated by adjusting

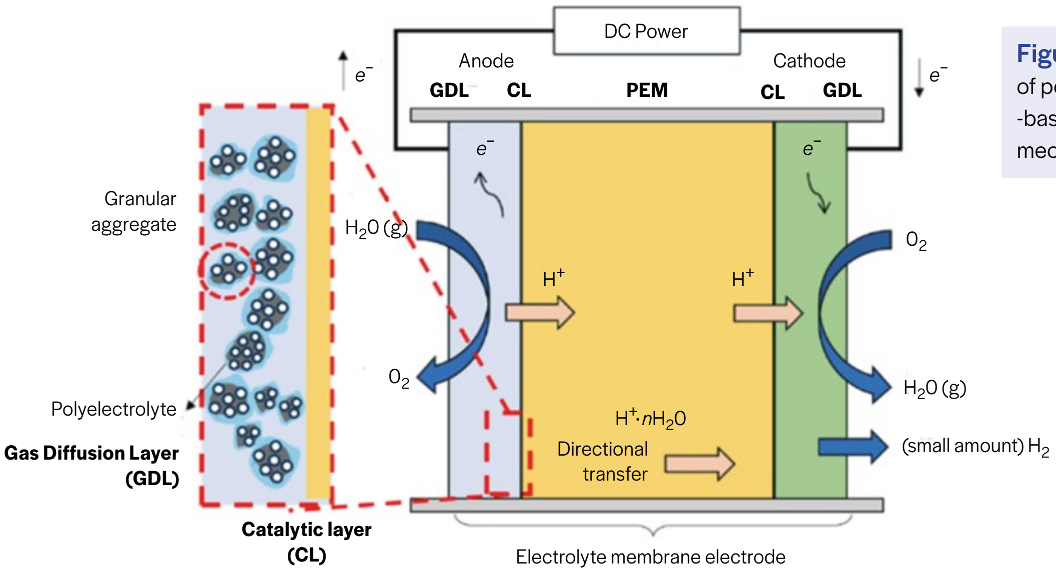



**Figure 9** | Schematic diagram of polymer electrolyte membrane -based air dehumidification mechanism.

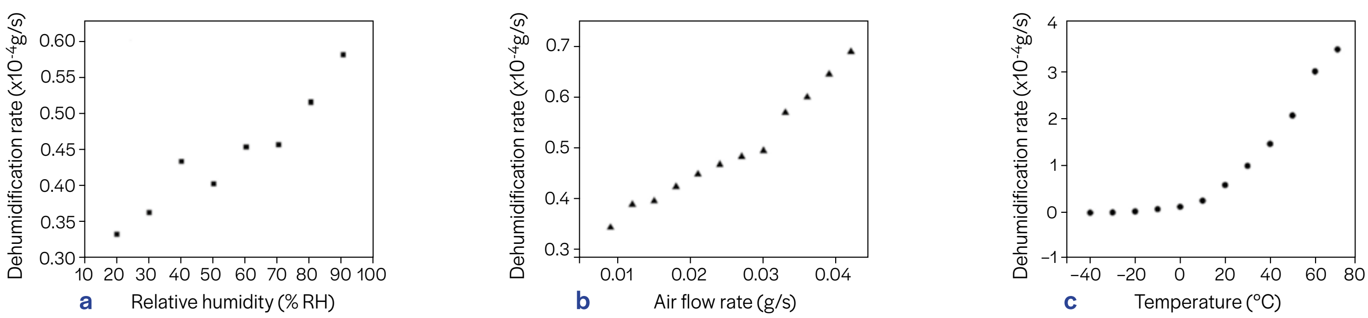



**Figure 10** | Variation in the dehumidification rate with the inlet air relative humidity **(a)**; flow rate **(b)**; and operating temperature of the dehumidification component **(c)**.

the DC voltage or current density, allowing for immediate response to load changes. Moreover, variations in electrical signals (voltage and current) can indirectly infer moisture loads, facilitating robust closed-loop control without the need for extensive external sensing. While inlet conditions, such as humidity, flow rate and temperature influence proton transport, the coordinated regulation of electrical inputs and air-side parameters ensures stable and predictable performance.

### 3.4.2 Hollow-fibre membrane dehumidification

Hollow-fibre membrane (HFM) dehumidification systems use microporous hollow fibres, (typically polytetrafluoroethylene (PTFE), polypropylene (PP), or polyvinylidene fluoride (PVDF), to separate moisture from air via selective vapour transport driven by vapour pressure differences (**Figure 11**)[29]. Often configured as shell-and-tube exchangers (**Figure 12**), permeated vapour is either absorbed by a liquid desiccant or removed under vacuum. Their compactness, ability to use low-grade waste heat, and inherent prevention of droplet entrainment make HFMs suitable for clean, stable environments ranging from spacecraft life support systems to industrial gas dehydration[30].

System performance is critically governed by pore size, mechanical strength, and surface wettability, driving extensive research into targeted surface modifications. To enhance water flux, hydrophilic treatments have shown remarkable results: Song *et al.*[25] coated PTFE fibres with polydopamine/PEI to achieve a flux of 2,109 L/($m^3$·h), while Wang *et al.*[32] employed a sacrificial template method to create super-hydrophilic surfaces with a flux of 1,477 L/($m^3$·h) without pore blockage. Conversely, to ensure operational stability, Su *et al.*[33] developed superhydrophobic PVDF membranes (contact angle 152.4°) via electrospinning, significantly improving anti-fouling capabilities in harsh conditions.

Complementing experimental advances, theoretical modelling has matured to support system design. Li *et al.*[34] developed a fully three-dimensional low-Re $k$–$\varepsilon$ turbulence model that accurately predicts coupled flow, heat, and mass transfer in HFM bundles. They obtained good agreement with experimental data for Reynolds numbers above 650. Operationally, vapour flux is modulated by controlling the transmembrane pressure difference via airflow rate, vacuum level, or desiccant conditions. While intrinsic membrane properties define the system's ultimate capacity, these extrinsic parameters allow for dynamic regulation to meet varying dehumidification demands.

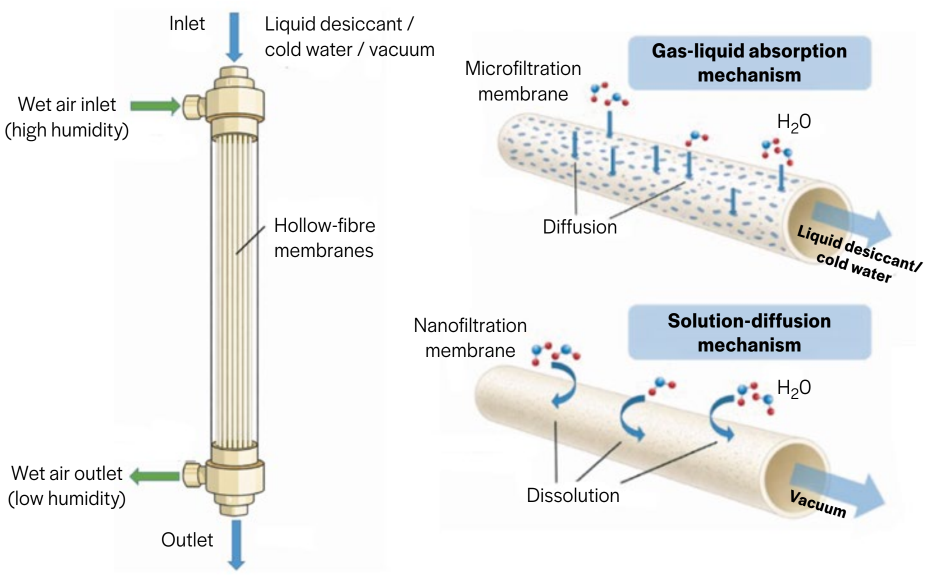



**Figure 11** | Schematic diagram of HFM dehumidification.

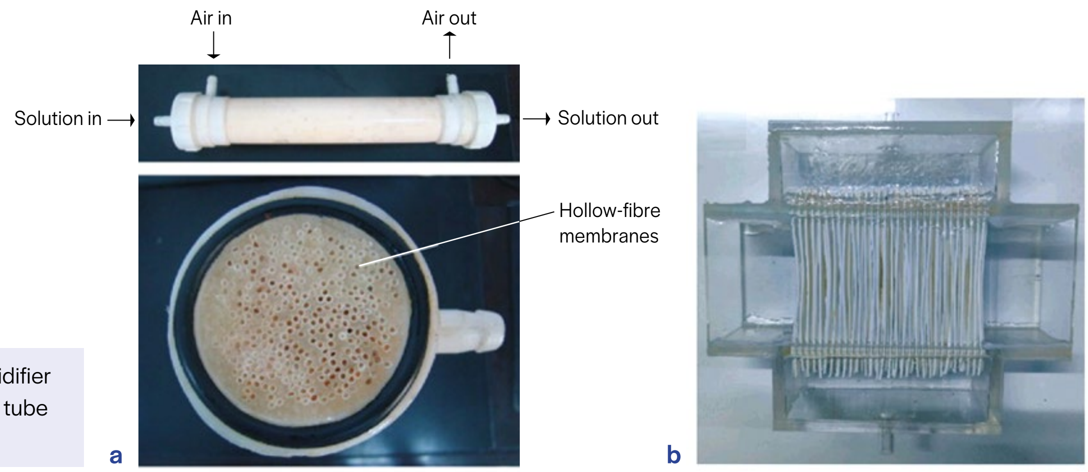



**Figure 12** | HFM dehumidifier components with shell and tube structure[31].

# 4 / Comparison and application

Different dehumidification technologies have distinct technical characteristics and application scenarios. Figure 13 illustrates the mapping of inlet versus outlet air humidity ratios under typical operating conditions. As observed, solid desiccant dehumidification and liquid desiccant dehumidification excel at deep-dehumidification, while vapour compression dehumidification shows great moisture removal capacity in humid conditions.

Table 1 summarises and compares the key performance characteristics, material features, technological maturity, market penetration, and future development directions of major dehumidification technologies. As shown in Table 1, vapour compression and solid desiccant systems currently exhibit the highest technology readiness and market penetration, remaining the prevailing choice for comfort air-conditioning and industrial applications. Liquid desiccant systems have also reached an advanced stage, increasingly adopted where thermal–humidity decoupling is critical. In contrast, membrane-based technologies (electrolyte and hollow-fibre) remain in the early stages of commercialisation. While their compact, electrically driven designs offer distinct advantages for precise, localised control, their current deployment is largely confined to niche scenarios. Widespread adoption hinges on advancements in material durability, cost reduction, and long-term stability.

From an engineering perspective, no single technology simultaneously optimises energy efficiency, dehumidification depth, simplicity, and lifecycle cost. Condensation systems are suitable for general comfort applications but are not ideal for deep dehumidification; solid desiccants excel in ultra-low humidity environments yet demand significant regeneration energy; liquid desiccants leverage low-grade heat for flexibility; and membrane systems provide compact, modular alternatives. Consequently, when choosing a technology, humidity precision, available energy sources, system scale, and economic constraints must be balanced.

Crucially, these technologies are complementary rather than mutually exclusive. Hybrid systems are often employed to reconcile efficiency, depth, and stability. For instance, battery manufacturing requires supply-air absolute humidity below 0.5 g/kg, which cannot be achieved with condensation or solid desiccants alone without excessive energy penalties. Figure 14 illustrates a typical integrated process for such drying rooms, where sequential humidity reductions on the psychrometric chart demonstrate the synergistic potential of combined approaches.

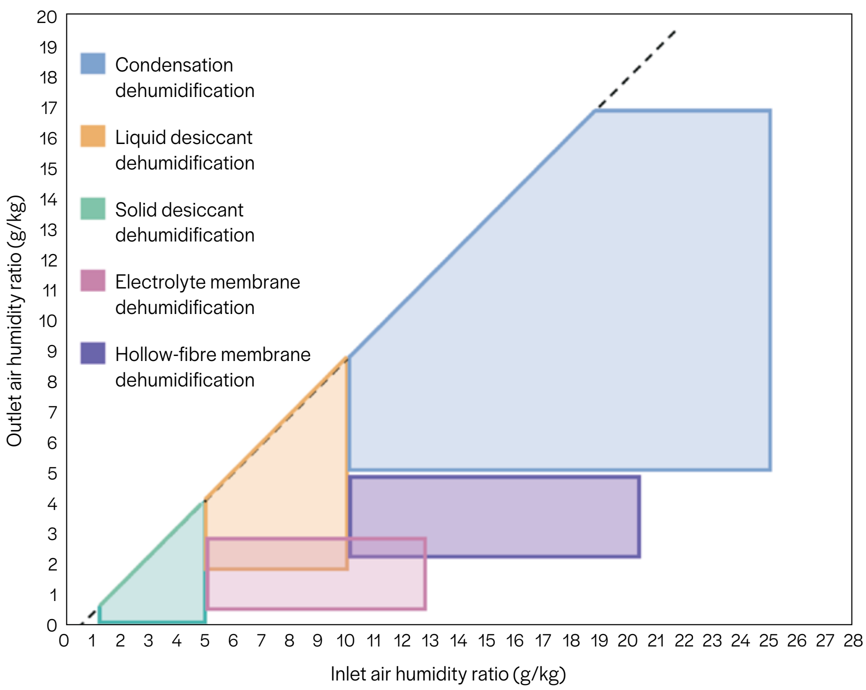



**Figure 13** | Typical inlet and outlet air humidity ratio ranges for various dehumidification technologies.

**TABLE 1 CHARACTERISTICS OF VARIOUS DEHUMIDIFICATION TECHNOLOGIES**

| | | VAPOUR COMPRESSION REFRIGERATION DEHUMIDIFICATION | THERMOELECTRIC DEHUMIDIFICATION | LIQUID DESICCANT DEHUMIDIFICATION | SOLID DESICCANT DEHUMIDIFICATION | ELECTROLYTE MEMBRANE DEHUMIDIFICATION | HOLLOW-FIBRE MEMBRANE DEHUMIDIFICATION |
|---|---|---|---|---|---|---|---|
| **Outlet air dew point (°C)[15]** | | 0~10 | 0~10 | −20~0 | −70~−10 | −60~−10 | −30~−0 |
| **Performance indicators** | | COPe[i] : 2.5~5.0[4],[15] | COPe: 0.4~0.7[6] | SEC[ii] :0.15~0.23 kWh/kg [15] | SEC:0.48~0.65 kWh/kg[15] | SEC:0.5~1.2 kWh/kg [15],[35] | SEC: 0.28~0.46 kWh/kg[15] |
| **Cutting-edge technologies** | **Material** | | $Bi_2Te_3/Sb_2Te_3$ | Ionic liquids (ILs) | Composite materials (LiCl@MOFs) | PEM + OER[iii] catalyst | Composite membranes (PES/Pebax, etc.) |
| | **Characteristics** | | ZT ≈ 1.0; cold-side temperature down to −40°C | Surface water vapour partial pressure approaches zero; low metal corrosion risk | Specific surface area > 3000 $m^2/g$ | Membrane thickness < = 200 ηm; stable operation from −20 to 70°C | Water vapour permeance > 1000 GPU[iv]; high selectivity |
| **Advantages** | | Mature technology; large moisture removal capacity under high-humidity conditions | No moving parts; easy maintenance; compact size | Air sterilisation capability; use of low-grade heat | Deep dehumidification (dew point down to −80°C) | Solid-state dehumidification; purely electric-driven; no condensate discharge | Isothermal dehumidification; high packing density |
| **Disadvantages** | | Independent humidity control not possible; frosting at low temperature | COP decreases with increasing current; high heat dissipation load | High corrosivity; liquid carryover (droplet entrainment) risk | High regeneration energy consumption; bulky system size | Polarisation losses; high material cost; small airflow capacity | Membrane fouling risk; leakage/permeation risk; pressure difference required across membrane |
| **Application Scenarios** | | Residential buildings, commercial buildings, general industrial environments | Portable devices, vehicle-mounted systems, micro sealed enclosures | Hospitals, food processing, large-volume fresh air systems | Lithium battery manufacturing, semiconductor fabrication, pharmaceutical industry | Aerospace, power switchgear cabinets, high-precision storage | Green buildings, distributed HVAC systems, fresh air pretreatment |
| **Market Penetration** | | > 70% | < 5% | < 10% | 10% ~ 20% | < 1% | < 5% |
| **Technology Readiness Level (TRL)** | | 9 | 8 | 8 | 9 | 5~6 | 6 |
| **Future Development Directions** | | Adoption of low-GWP refrigerants; optimisation via variable-frequency (inverter) technology | Development of nanostructured materials with ZT > 2.0 | Membrane-based liquid desiccant systems to eliminate carryover risk | Development of low-temperature regeneration and waste-heat-driven adsorbents | Reduction of membrane cost; improved durability under harsh environments; enhancement of non-fluorinated membrane performance | Enhanced anti-fouling capability; improved long-term stability |

i Electrical coefficient of performance: Ratio of the cooling capacity to the consumed electrical energy.

ii Specific energy consumption: Energy consumed per unit mass of water removed.

iii Oxygen Evolution Reaction: The anodic electrochemical process of water oxidation, generating oxygen gas, protons, and electrons under an applied potential.

iv Gas Permeation Unit: A unit used to quantify gas permeance through membranes, where 1 GPU = $10^{-6}$ $cm^3$ (STP)/ ($cm^2 \cdot s \cdot cmHg$); STP denotes standard temperature and pressure, defined as 0 °C and 1 atm).

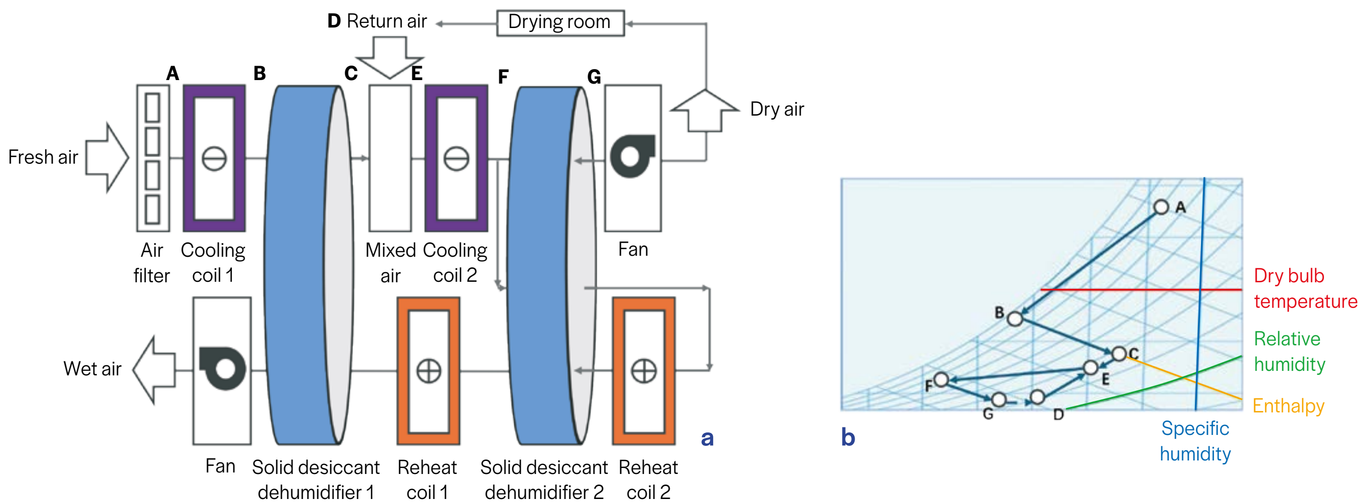



**Figure 14** | Battery manufacturing drying room air handling systems. **(a)** Flow chart. **(b)** Psychrometric chart.

# 5 / Conclusion and prospects

This technical brief summarised major dehumidification technologies from the perspectives of performance characteristics, technological maturity, and engineering applicability. The analysis confirms that technology selection is strongly application-dependent, as no single solution can simultaneously optimise humidity precision, energy efficiency, system complexity, and lifecycle cost.

Current large-scale practice is primarily supported by established refrigeration and desiccant-based systems, while membrane technologies are emerging as complementary solutions in specialised or compact applications. Increasing industrial precision requirements and energy-efficiency targets are accelerating the adoption of integrated and hybrid configurations tailored to specific operating conditions.

Looking forward, technological progress over the next 5 to 10 years is expected to focus mainly on improving the efficiency and sustainability of established systems through enhanced regeneration strategies and material optimisation, rather than complete technological substitution. Over the course of 10 to 20 years, breakthroughs in cutting-edge desiccant materials and state-of-the-art membranes may expand the role of compact and electrically driven systems. Nevertheless, considering current maturity levels and infrastructure compatibility, condensation and solid desiccant technologies are likely to remain the mainstream solutions for large-scale applications in the foreseeable future.

## 5.1 The IIR's recommendations

Efficient dehumidification is essential for improving thermal comfort and reducing energy consumption and greenhouse gas emissions from air-conditioning systems. To advance global climate adaptation, mitigation, and energy-efficient cooling, the IIR recommends the following actions:

1. Prioritise humidity control to elevate cooling source temperatures. By integrating efficient dehumidification technologies, air-conditioning systems can operate at higher chilled-water or evaporating temperatures. This shift significantly reduces energy demand and boosts overall system efficiency by lowering the required temperature lift.
2. Accelerate the deployment of efficient dehumidification in hot-humid regions. With the surge in cooling demand concentrated in tropical and subtropical climates (e.g. Southeast Asia, Latin America, and coastal Africa), promoting advanced dehumidification is critical. Such measures enhance local climate resilience while mitigating the risks of excessive energy use, carbon emissions, and grid instability associated with conventional cooling expansion.
3. Support the further development and deployment of novel, emerging dehumidification technologies through technical alliances and funding mechanisms. Collaborative initiatives, targeted research programs, and financial support can accelerate the maturation and commercialisation of innovative dehumidification solutions, including advanced desiccants, membrane systems, and hybrid processes, thus enabling more sustainable and resilient cooling strategies worldwide.

## 5.2 Key actions for policy makers

1. **Promoting adoption of appropriate dehumidification technologies in tropical and high-humidity regions**. In these regions where the demand for air conditioning is rapidly increasing, humidity control is often more critical than temperature reduction. Independent temperature and humidity handling systems or separate sensible and latent cooling systems can prevent the energy waste typical of traditional systems that "cool first and then reheat". Financial incentives and subsidies should also be tailored to favour high-efficiency dehumidification systems that meet stringent humidity control standards tailored for hot and humid climates.

2. **Advancing development of global air-conditioning test standards that fully incorporate humidity control metrics**. Current energy efficiency standards primarily focus on temperature regulation and often neglect dehumidification performance. Establishing energy efficiency testing methods that take moisture removal performance into account is essential. International collaboration with bodies like ISO, CENELEC, ASHRAE, and JSRAE is needed to create unified global testing conditions that reflect various humidity scenarios (e.g., high humidity, moderate humidity).

3. **Increasing support for research and development in innovative dehumidification technologies**. Policy should channel funding into breakthroughs such as innovative dehumidification materials. The application of AI for dynamic humidity control, using sensors and algorithms to optimise operation and prevent over-dehumidification, should be encouraged.

# Abbreviation and nomenclature

| ABBREVIATIONS | |
|---|---|
| AC | Air conditioning |
| CL | Catalyst layer |
| COP | Coefficient of performance |
| $COP_e$ | Electrical coefficient of performance |
| $COP_t$ | Thermal coefficient of performance |
| GDL | Comprising gas diffusion layer |
| GPU | Gas permeation unit |
| GWP | Global warming potential |
| IL | Ionic liquid |
| MOF | Metal–organic framework |
| OER | Oxygen evolution reaction |
| PEBA | Polyether block amide |
| PEI | Polyethyleneimine |
| PEM | Proton exchange membrane |
| PES | Polyester |
| PP | Polypropylene |
| PSA | Pressure swing adsorption |
| PTFE | Polytetrafluoroethylene |
| PVDF | Polyvinylidene fluoride |
| RH | Relative humidity |
| SEC | Specific energy consumption |
| TEM | Thermoelectric module |
| TER | Thermoelectric refrigeration |
| TRL | Technology readiness level |
| VCR | Vapour compression refrigeration |

| NOMENCLATURE | |
|---|---|
| $CaCl_2$ | Calcium chloride |
| $H^+$ | Protons |
| LiBr | Lithium bromide |
| LiCl | Lithium chloride |
| $t$ | Temperature |
| $\omega$ | Humidity ratio |
| **SUBSCRIPT** | |
| a | Air |
| e | Equilibrium status of solution |
| s | Hygroscopic solution |
| ZT | Figure of merit |

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