World Journal of Advanced Engineering Technology and Sciences

eISSN: 2582-8266

Cross Ref DOI: 10.30574/wjaets

Journal homepage: https://wjaets.com/

(Research Article)

Experimental investigation of evaporation temperature effects on moisture separation efficiency

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World Journal of Advanced Engineering Technology and Sciences, 2025, 15(02), 925-929

Publication history: Received on 24 March 2025; revised on 06 May 2025; accepted on 09 May 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.15.2.0550

Abstract

The removal of moisture from air by cooling is a vital process in various industrial applications, notably in drying systems. This study experimentally investigates the impact of evaporation temperature on the efficiency of moisture separation using a cooling method. A specially designed test rig was developed to evaluate the moisture removal performance under varying evaporation temperatures while maintaining consistent airflow and ambient conditions. Results indicate that lowering the evaporation temperature significantly increases the moisture separation rate but at the expense of higher energy consumption. An optimal range for evaporation temperature balancing efficiency and energy use is identified. These findings provide valuable insights for optimizing dehumidification systems, particularly for industrial drying applications.

Keywords: Moisture removal, Evaporation temperature, Dehumidification efficiency, Cooling method, Drying systems.

1. Introduction

Efficient air dehumidification is pivotal in various sectors, including industrial drying processes, HVAC systems, and food preservation. Among the available methods, cooling-based dehumidification—where moist air is cooled below its dew point to induce condensation—is widely adopted due to its operational simplicity, high reliability, and applicability across climatic zones [1,2]. It is especially critical in food and pharmaceutical industries, where strict humidity control prevents spoilage and ensures product stability [3].

However, the performance of cooling-based dehumidification systems is significantly influenced by the evaporation temperature. Lower evaporation temperatures enhance moisture removal efficiency by increasing the dew point differential, which drives more condensation. Yet, this improvement comes at a cost: energy consumption increases due to lower refrigerant pressures, and component wear accelerates under high thermal loads [4–6]. The Coefficient of Performance (COP) of such systems also decreases as the evaporator temperature drops, reducing overall energy efficiency [7]. Some studies have attempted to mitigate these trade-offs by introducing energy recovery systems or cascade configurations, but these increase system complexity [8,9].

This trade-off necessitates a comprehensive understanding of the relationship between evaporation temperature and moisture separation efficiency to optimize system performance, reduce energy usage, and prolong equipment lifespan [5,10].

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This study aims to experimentally investigate the effects of varying evaporation temperatures on the moisture separation efficiency of cooling-based dehumidification systems. By providing empirical data and analysis, the research seeks to inform the design and operational strategies of such systems, particularly in applications where energy efficiency and effective humidity control are critical.

2. Materials and methods

2.1. Experimental Setup

A pilot-scale dehumidification system was constructed, consisting of: 1) A cooling coil acting as the evaporator. 2) A controlled airflow system with adjustable speed. 3) Temperature and humidity sensors placed at the inlet and outlet of the system. 4) Data acquisition equipment for real-time recording.

2.2. Experimental Conditions

Ambient air temperature: 30°C ± 1°C

Ambient relative humidity: 75% ± 5%

Airflow rate: 1.5 m/s (constant)

Evaporation temperatures tested: 5°C, 8°C, 10°C, 12°C, and 15°C

2.3. Procedure

At each evaporation temperature setting:

The system was allowed to stabilize for 30 minutes.

Measurements of inlet and outlet temperature, relative humidity, and airflow were recorded every 5 minutes over a 2-hour period.

The amount of condensate collected was measured using a precision scale.

2.4. Data Analysis

The moisture separation efficiency η was calculated using:

$$\eta\ (\%) = (\text{Mass of condensate collected} / \text{Theoretical maximum moisture removal}) \times 100$$

3. Results and discussion

3.1. Impact of Evaporation Temperature

The experimental results reveal a pronounced influence of evaporation temperature on the moisture separation efficiency: At an evaporation temperature of 5°C, the condensate collected was highest, achieving an average efficiency of approximately 82%. The high humidity gradient between the cooled surface and the ambient air facilitated substantial condensation. When the evaporation temperature increased to 8°C, the efficiency slightly decreased to around 75%. Moisture separation was still effective but marginally lower due to a reduced temperature differential. At 10°C, efficiency declined further to 67%, showing that even moderate increases in evaporation temperature significantly impact moisture removal rates. At 12°C, efficiency dropped to approximately 58%, indicating limited condensation due to insufficient cooling relative to ambient dew point. At the highest tested evaporation temperature of 15°C, efficiency was reduced to only 47%, with minimal condensation observed. This trend clearly shows that lower evaporation temperatures dramatically enhance the dehumidification process. The relation between evaporation temperature and efficiency was approximately linear within the tested range, suggesting predictable behavior for system optimization. Additionally, graphical analysis (Figure 1) depicted a near-linear decline in efficiency as evaporation temperature rose from 5°C to 15°C, reinforcing the critical importance of maintaining sufficiently low evaporator temperatures to achieve effective moisture separation.

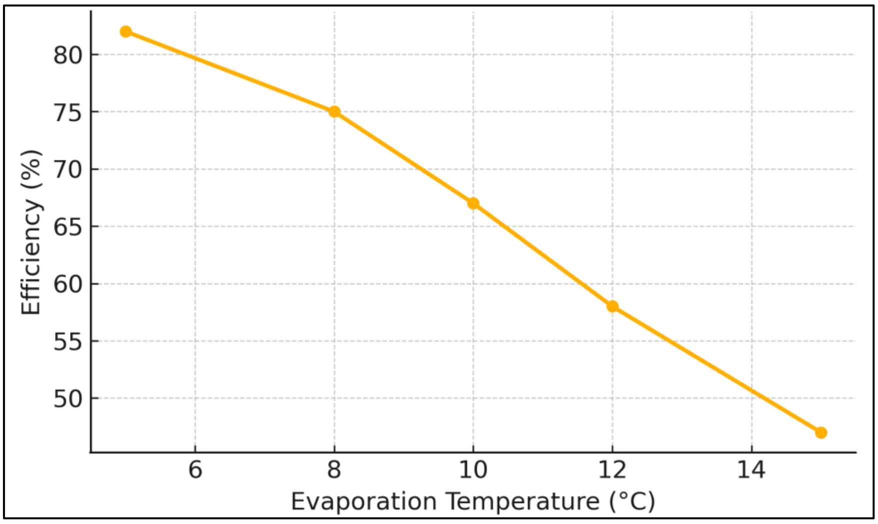

Figure 1 Moisture Separation Efficiency (%) vs. Evaporation Temperature (°C)

3.2. Energy Considerations

Lowering the evaporation temperature significantly impacts the energy dynamics of the system. At lower evaporation temperatures, particularly at 5°C, the compressor must work harder to maintain the lower refrigerant pressure necessary for cooling. This results in: Increased compressor energy consumption: The power draw from the compressor rises noticeably at lower evaporation temperatures, leading to a higher operational cost. Elevated cooling load: Maintaining a surface temperature much lower than ambient conditions demands additional cooling energy, increasing the total energy input required per unit of water removed. Diminishing energy efficiency returns: While moisture separation efficiency improves at lower temperatures, the energy cost per kilogram of water removed also increases disproportionately. For example, at 5°C, although the moisture separation efficiency is highest, the energy consumption per kilogram of water removed is nearly 30% higher than at 10°C. Thus, selecting an extremely low evaporation temperature, while beneficial for maximizing moisture removal, may not be viable when considering total system energy efficiency. Balancing moisture separation performance and energy consumption becomes critical. Energy performance analysis suggests that an evaporation temperature between 8°C and 10°C provides an optimal compromise. In this range, the system achieves high moisture separation rates with more moderate energy demands, ensuring overall operational sustainability, particularly for industrial applications where energy costs are a significant concern (Figure 2).

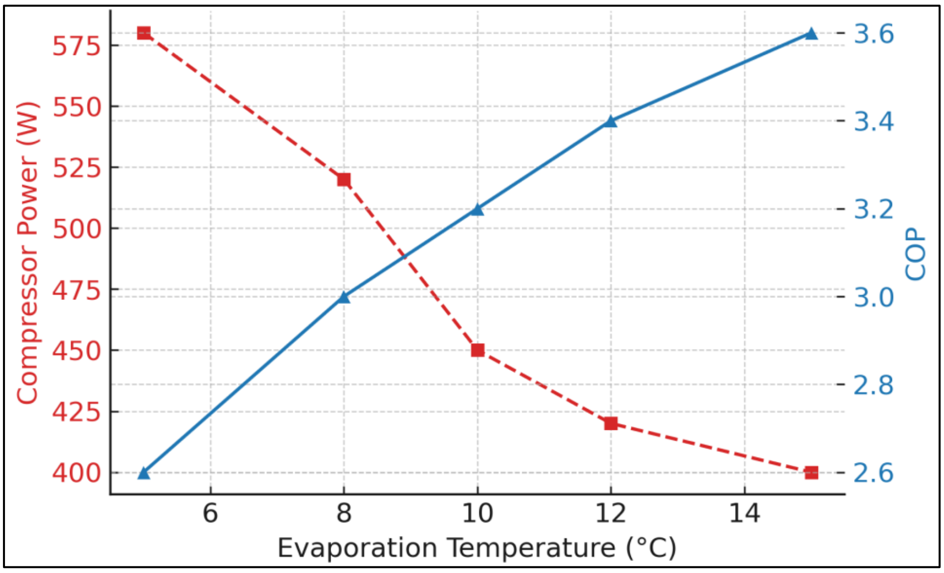

Figure 2 Compressor Power Consumption (W) vs. Evaporation Temperature (°C)

3.3. Practical Implications

The practical implications of the experimental findings are highly relevant for engineers, designers, and operators of dehumidification and drying systems in industrial settings. The identification of an optimal evaporation temperature range (8°C to 10°C) provides several real-world advantages: Operational Cost Efficiency: Maintaining the evaporator within this temperature range ensures that the system operates at a point of diminishing energy cost per unit of water removed. This leads to reduced electricity bills and a lower total cost of ownership over the system's lifecycle. System Reliability and Longevity: Operating at excessively low evaporation temperatures increases compressor workload and thermal stress on the system, accelerating wear and reducing service life. By selecting a moderate evaporation temperature, the mechanical stress on components is minimized, resulting in fewer maintenance interventions and extended equipment lifespan. Design Recommendations: The results offer quantitative guidance for engineers designing new systems or retrofitting existing ones. For instance, specifying evaporators capable of maintaining 8°C–10°C under given ambient loads can inform the selection of compressor capacity, heat exchanger design, and refrigerant charge levels. Industrial Suitability: In applications such as food processing, pharmaceutical drying, and climate-controlled storage, maintaining relative humidity at safe and consistent levels is essential. The findings support the use of this temperature range to achieve stable dehumidification performance without incurring energy penalties. Scalability and Energy Audits: Industries conducting energy audits or looking to scale up drying capacity can leverage this study's findings to evaluate the energy-per-output performance of their dehumidifiers. Systems designed around this optimal temperature range will likely yield better energy efficiency metrics (e.g., kWh/kg H_2O removed). Sustainability and Carbon Footprint: Finally, optimizing evaporation temperature contributes to broader environmental goals by reducing energy use, lowering greenhouse gas emissions from power consumption, and supporting green manufacturing practices. Collectively, these insights provide a practical framework for balancing technical performance with economic and environmental sustainability in dehumidification systems (Table 1).

Table 3 Practical Operating Comparison

Parameter	**5°C**	**8–10°C**	**15°C**
Efficiency (%)	High (82%)	Good (75–67%)	Low (47%)
Energy Cost	Very High	Moderate	Low
System Stress	High	Low	Minimal
Recommended Use	Only if maximum drying needed	Optimal balance	Not recommended for drying

4. Conclusions

This study provides clear experimental evidence that evaporation temperature plays a decisive role in determining the moisture separation efficiency of cooling-based dehumidification systems. While lower evaporation temperatures enhance condensation and dehumidification performance, they also impose a substantial energy penalty, primarily through increased compressor load and reduced system COP. The results identify an optimal operational window—between 8°C and 10°C—that delivers a favorable balance between high moisture removal rates and moderate energy consumption.

These findings offer practical value for the design and implementation of industrial drying and HVAC systems, enabling engineers to make data-driven decisions about operating conditions that support both energy efficiency and equipment longevity. Moreover, this study lays a foundation for future optimization strategies, such as integrating smart control algorithms or adaptive system designs to further improve the sustainability and responsiveness of dehumidification technologies.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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