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Removal of moisture from air by cooling method

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Abstract

Moisture removal from air is a critical aspect of climate control in various industrial and residential applications. The cooling method, which relies on the condensation of water vapor by lowering air temperature below its dew point, is one of the most commonly used techniques for dehumidification. This study investigates the principles, effectiveness, and limitations of the cooling method in different environmental conditions. By examining the impact of factors such as ambient temperature, humidity levels, and cooling system design, this research aims to identify strategies for optimizing energy efficiency in dehumidification processes. Experimental results highlight the correlation between cooling temperature and condensation rates, emphasizing the need for advanced cooling technologies to reduce energy consumption. The findings contribute to the development of more sustainable and cost-effective dehumidification systems, offering valuable insights for enhancing HVAC performance and reducing environmental impact.

Keywords: Air; Cooling; Moisture; Removal; Saturated

1. Introduction

Moisture control in the air is essential in various industrial and residential applications, as excessive humidity can negatively impact processes, equipment, and air quality. High levels of moisture in the air can lead to problems such as corrosion, mold growth, and reduced efficiency in heating, ventilation, and air conditioning (HVAC) systems [1]. Thus, efficient methods for moisture removal are crucial in maintaining optimal conditions in diverse environments.

The cooling method, also known as condensation dehumidification, is one of the most widely adopted techniques for removing moisture from the air. This approach operates by cooling the air to a temperature below its dew point, causing water vapor to condense into liquid form, which can then be easily collected and removed [2]. The process is straightforward, making it a preferred choice in both industrial and residential settings where humidity control is necessary [3]. However, this method's effectiveness and energy efficiency can be significantly influenced by environmental conditions, including ambient temperature and relative humidity levels [4].

While the cooling method is widely used, its energy consumption remains a primary concern, especially in hot and humid climates where the demand for cooling increases exponentially [5]. Recent studies have focused on optimizing this dehumidification process by exploring advanced cooling technologies, heat exchangers, and alternative refrigerants to enhance efficiency and reduce energy costs [6, 7]. The development of energy-efficient cooling systems can significantly reduce operational expenses and minimize the environmental impact of moisture control methods.

This paper aims to examine the principles, effectiveness, and limitations of the cooling method for moisture removal from the air. By analyzing the relationship between cooling temperature, humidity levels, and condensation rates, this study seeks to propose strategies for enhancing the efficiency of this widely used dehumidification technique. The

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findings from this research could contribute to advancing sustainable cooling methods that are both cost-effective and environmentally friendly.

2. Materials and methods

2.1. Materials

Since this is a review paper, no physical materials were directly used. Instead, the study relied on: 1) Published Articles and Research Papers: Peer-reviewed journal articles and technical reports; 2) Analytical Tools: Software tools like Mendeley and Zotero were used for reference management and to organize the extracted data; 3) Data Analysis Software: Tools such as Microsoft Excel and statistical analysis software were utilized to perform a comparative analysis of quantitative data from different studies.

2.2. Methods

Literature Search: A comprehensive literature search was conducted to gather relevant studies on the removal of moisture from air using the cooling method. The search focused on peer-reviewed articles, technical papers, and review studies published in reputable journals. The following databases were used for the search: IEEE Xplore, ScienceDirect, Google Scholar, Web of Science, SpringerLink. The keywords used in the search included "cooling-based dehumidification," "moisture removal from air," "condensation methods," "humidity control," and "energy efficiency in cooling systems". Exclusion Criteria: Studies that did not specifically address cooling methods, articles that focused solely on non-cooling-based dehumidification techniques, and publications without peer-review standards.

3. Results and discussion

3.1. Condensation

3.1.1. Overview of moisture condensation

The process of condensing moisture in the air is a very complex process, especially the heat exchange process during condensation, because there is a phase change from the vapor phase to the liquid phase called exothermic condensation of moisture. The process of condensation can only occur when the vapor is in a state below the limit due to cooling or compression. If the condensation process is carried out at a temperature and pressure above the triple point of the given substance, the vapor is condensed into a liquid state. The area where the condensation process occurs can be in the volume of the vapor mass when the temperature is lower than the saturation temperature at the corresponding pressure or can also occur on the surface of the cooled object [8]. In reality, we often encounter the process of vapor condensing into a liquid state on a solid surface, for example, the process of vapor condensation on the surface of the evaporator of a refrigeration device, or a glass of ice left out in the air for a while, water will condense around the glass of ice... or the phenomenon of condensation in air conditioners, dehumidifiers or civil and industrial air conditioners [8].

3.1.2. Characteristics of the condensation process

The process of condensation of the refrigerant vapor is associated with phase change. For the condensation process on the surface of a solid object, the following conditions must be met:

The surface temperature of the device (solid object) must have a low temperature, the saturated vapor of the humid air must be in contact with each other [8]. The surface must have condensation centers such as large enough roughness, dust and air bubbles to avoid the surface being too smooth [8]. Depending on the surface state and wettability of the liquid, the process of condensation on the surface of a solid object includes: film condensation and droplet condensation; Film condensation is when the liquid droplets condense together into a film on the surface of a solid object, film condensation occurs when the liquid completely wets the surface of a solid object, the wetting angle is less than $\pi / 2$ [8]. Droplet condensation is when the liquid droplets condense separately on the surface of a solid object. Occurs when the liquid does not wet the surface of a solid object, the surface is smooth or has a layer of grease on the surface [8].

3.2. Humid air

3.2.1. Concept

Humid air (atmosphere) is a mixture of dry air and water vapor.

Dry air is a mixture of gases with the following volumetric composition: Nitrogen about 78%; Oxygen: 21%; CO_2, H_2O and other inert gases account for about 1%.

Water vapor in humid air has a very small partial pressure (about 15 to 20 mmHg), so at normal temperature, water vapor in the atmosphere is superheated, we consider it an ideal gas. Thus, humid air can be considered an ideal gas mixture, and the formulas of ideal gas mixtures can be used to calculate humid air.

3.2.2. Classification of humid air

Saturated humid air: Saturated humid air is humid air in which the amount of water vapor reaches the maximum value $G = G_{max}$, meaning that saturated humid air cannot receive any more water vapor.

Unsaturated humid air: Unsaturated humid air is humid air in which the amount of water vapor has not reached the maximum value $G < G_{max}$, meaning that it can still receive a certain amount of water vapor before becoming saturated humid air.

Supersaturated humid air: Supersaturated humid air is humid air in which, in addition to the maximum amount of water vapor G_{hmax}, there is also an additional amount of condensed water contained in it. The water vapor here is saturated humid steam.

If more water vapor is added to saturated humid air, that amount of water vapor will condense into water, then the saturated humid air becomes supersaturated air. For example, fog is supersaturated humid air because it contains condensed water droplets.

3.2.3. Physical parameters of humid air

a. Air pressure

The pressure of moist air is equal to the sum of the partial pressure of dry air P_k and the partial pressure of water vapor P_h.

$$P = P_k + P_h \qquad (2.1)$$

b. Temperature

The temperature of moist air is equal to the temperature of dry air T_k and equal to the temperature of water vapor T_h.

$$T_a = T_k = T_h \qquad (2.2)$$

c. Humidity

Absolute humidity

Absolute humidity is the mass of water vapor contained in 1m^3 of moist air. This is also the density of water vapor in moist air.

$$\rho_h = \frac{G_h}{V}, \text{ kg/m}^3 \qquad (2.3)$$

Relative humidity

Relative humidity "φ" is the ratio of the absolute humidity of unsaturated air to the absolute humidity of saturated humid air $\rho_{h\max}$ at the same temperature.

$$\varphi = \frac{\rho_h}{\rho_{h\max}} \qquad (2.4)$$

From the equation of state of unsaturated humid air: $p_hV=G_hR_hT$ and saturation: $p_{hmax}V = G_{hmax}R_hT$, infer:

$$\rho_h = \frac{G_h}{V} = \frac{p_h}{R_hT} \qquad \text{(a)}$$

and $$\rho_{h\max} = \frac{G_{h\max}}{V} = \frac{p_{h\max}}{R_hT} \qquad \text{(b)}$$

Divide (a) by (b) to get:

$$\varphi = \frac{\rho_h}{\rho_{\max}} = \frac{p_h}{p_{\max}}$$

Since $0 \le p_h \le p_{hmax}$, $0 \le \varphi \le 100\%$. Dry air has $\varphi=0$, saturated humid air has $\varphi=100\%$.

The most suitable humidity for animal health is $\varphi = (40 \div 75)\%$, for cold storage of food is 90%.

Vapor capacity

Vapor capacity d is the amount of vapor contained in humid air corresponding to 1 kg of dry air.

$d = G_h/G_k$; (kgh/kgK) (2.5)

From the ideal gas state equation written for water vapor and dry air:

$$G_h = \frac{p_hV}{R_hT} \text{ và } G_k = \frac{p_kV}{R_kT} \qquad (2.6)$$

Substitute the values of G into (*) and get:

$$d = \frac{p_hR_k}{p_kR_h} = \frac{8314.18.p_h}{29.8314.p_k} = 0,622\frac{p_h}{p-p_h};\left[kgh/kgK\right] \qquad (2.7)$$

Enthalpy of humid air

The enthalpy of moist air is equal to the sum of the enthalpy of dry air and the enthalpy of water vapor contained in it. In engineering, the enthalpy of 1 kg of dry air and d kg of water vapor contained in (1+d) kg of moist air is usually calculated, denoted by i:

$I = i_k + d.i_h$ (kj/kgK) (2.8)

In there:

i_k: entanpi of 1kg dry air, $i_k = C_{pk}t$, and C_{pk}= 1Kj/kgK. Thus $i_k=t$

i_h: The enthalpy of steam, if the moist air is not saturated, the steam is superheated steam

$i_h = 2500 + C_{ph}t = 2500 + 1.9t$; (2.9)

Therefore:

$I = t + d(2500+1.93t)$; (kJ/kgK) (2.10)

3.3. I-d Humid Air State Graph

In 1918, Russian scientist: Ramzyn proposed the idea of I-d graph. In 1923, German scientist: Molier published a similar graph, I-x graph. Established with two coordinate axes I and d forming an angle 135° (Fig. 1).

- → **d** = const: is vertical.
- → **I** = const: are lines that make an angle with the OI axis 135°.

Each I-d graph is constructed with a certain pressure value and is clearly marked on the graph → There is a family of I-d graphs..

The line φ = 100% divides the graph into two regions:

- → Zone I: unsaturated humid air.
- → Zone II: oversaturated humid air (fog zone)

All points on the line φ = 100%, representation of saturated humid air.

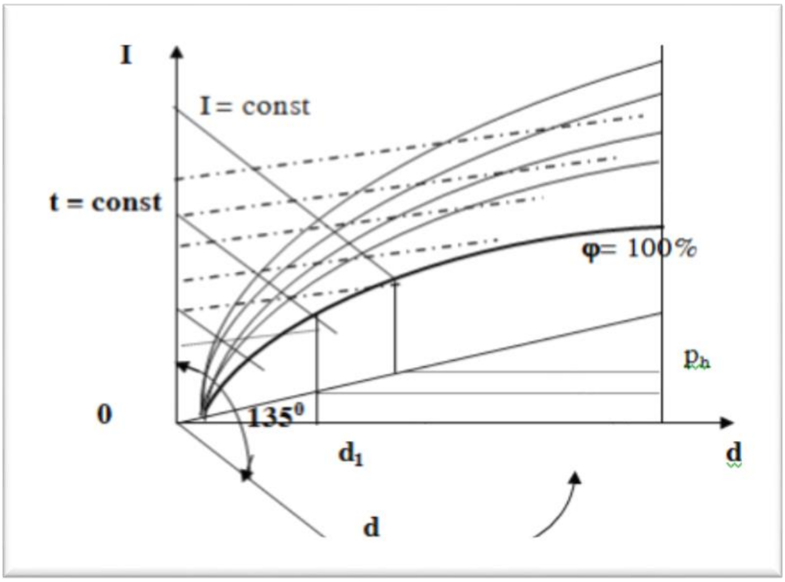

Figure 1 I-D diagram of humid air

3.4. Some basic processes on i - d graph

The process of changing the state of air

3.4.1. Heating process (d = const)

Non-humidifying heating process (d=const): is the process of heating humid air, which occurs thanks to the heat exchanger also known as Calorifer in the drying system. The air at point A has temperature t_A, relative humidity φ_A, heated without increasing humidity to temperature t_B. The characteristic of the heating process is that the temperature can increase ($t_A < t_B$) but the moisture content d remains unchanged and the relative humidity decreases. ($\varphi_A > \varphi_B$) (Fig. 2). So the state after heating is determined by the intersection point B of the tB line and $d_B = d_A$. The increase in temperature and decrease in humidity make the air not only able to provide heat to the drying material in convection dryers but also increase the ability to absorb more moisture or the drying capacity. Heat loss or heat received by the air in the calorifer:

$$q_{AB} = I_B - I_A \text{ [kJ/kg KK]} \qquad (2.11)$$

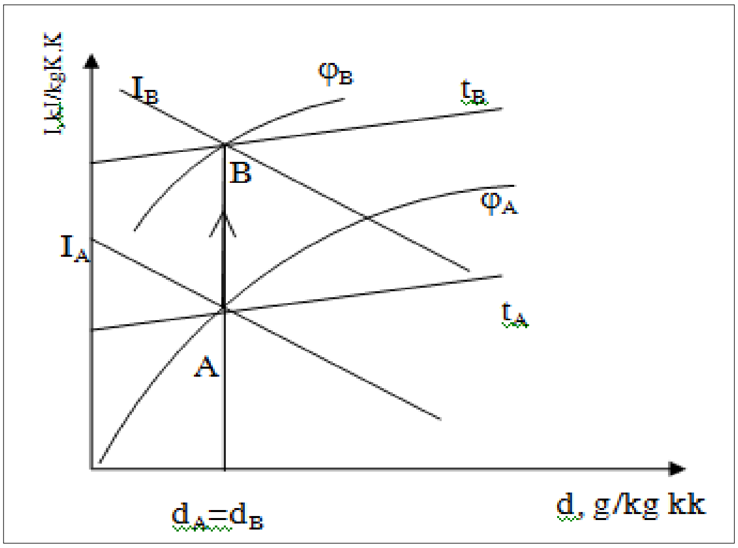

Figure 2 Representation of air heating process on i-d graph

3.4.2. Some processes of cooling humid air

Isohumid cooling process

This process occurs when humid air in a certain state loses heat due to heat exchange with the environment. Therefore, the amount of moisture remains constant. The air at point A is cooled according to the process d = const, to the dew point temperature t_{s2}, then the dew point B_2 will be the intersection of the line d_A = d = const and the line φ = 100%. Similarly, if the air at point B2 continues to be cooled, the dehumidification process will begin (Fig. 3).

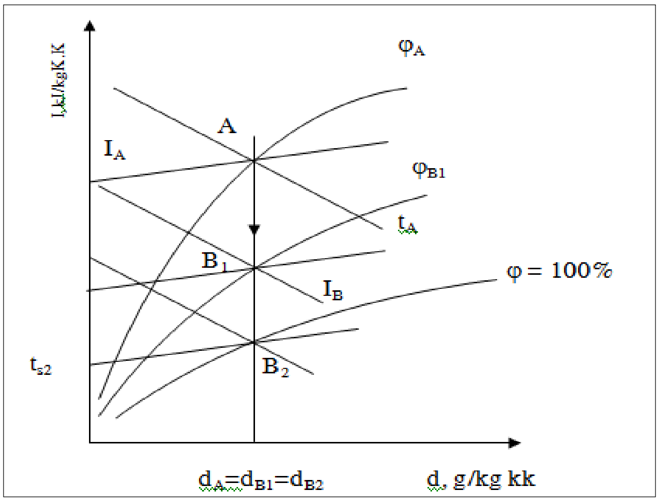

Figure 3 Representation of the cooling process of isohumid air

Cooling and dehumidification process

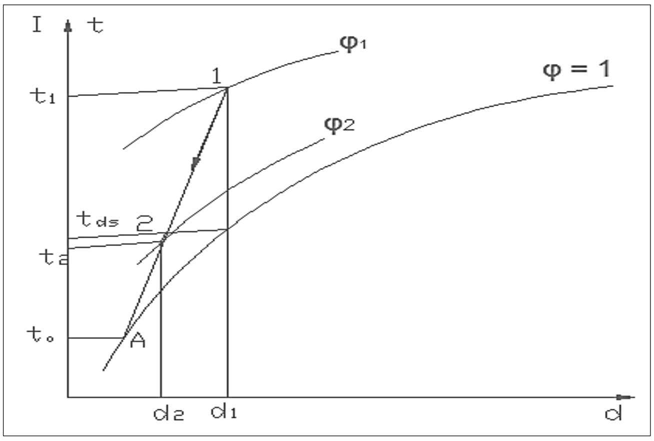

Figure 4 Representation of the dehumidifying air cooling process on the i-d graph

Humid air after being cooled and dehumidified from its initial state has a temperature and humidity of 1 (t_1, φ_1) after cooling to state 2 (t_2, φ_2), has $d_2 < d_1$ and $\varphi_1 < \varphi_2 = 95\%$. The amount of condensate on the surface of the evaporator is calculated by the formula:

$W = G(d_1 - d_2) = L(d_1 - d_2)$ kg/s (2.12)

The dehumidification cooling process has a moisture content d (g/kgk) decreasing from d_1 to d_2 and reducing the partial pressure of water vapor in the drying agent. Therefore, this method is very effective in the field of cold drying. To apply this device in the cold drying method, people create a difference between the saturated pressure of water vapor on the surface of the VLS and the partial pressure of water vapor in the TNS by reducing the partial pressure of water vapor in the TNS. This is done by reducing the moisture content of the air by separating moisture in the evaporator. At that time, moisture moves to the surface and from the surface to the surrounding environment can occur at temperatures greater or less than 0°C. With the cold drying method, due to contact with air with low humidity and partial pressure of water vapor, a large difference is created between the partial pressure of water vapor in the TNS and that of the surface layer of the VLS, promoting rapid drying speed. It can also be said that here the temperature gradient and pressure gradient have the same sign, so the temperature gradient does not inhibit the moisture migration process like hot drying, but on the contrary, it has the effect of enhancing the moisture migration from inside the VLS to the surface and evaporating into the TNS, shortening the drying time.

3.5. Diffusion evaporation method

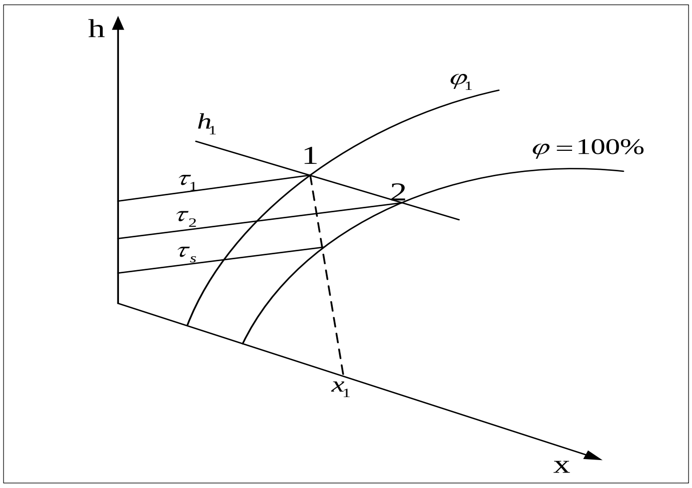

Figure 5 h – x (I – d) graph of humid air

1- initial state of air; 2 – moisture reaches saturation state; t_1 - dry temperature; t_2 - wet temperature; t_s- dew point temperature

A typical example of diffusion evaporation is the evaporation of water vapor into air. When water is continuously sprayed and the dry air has the same temperature, the water will diffusely evaporate into the air and the state of the air will change according to the enthalpy line: (h) = const. Represent the process of cooling by diffusion evaporation of water into dry air on the graph of enthalpy h – vapor content x of the humid air.

From point 1 which is the initial state of the air to point 2, the humidity increases from: $\varphi_1 \longrightarrow \varphi_{\max} = 100\%$. In this way we carry out the process of cooling the air. The temperature decreases from: t_1 to t_2. The temperature t_1 is read on the dry thermometer and t_2 is the temperature read on the wet thermometer.

Application in refrigeration engineering is diffusion absorption refrigeration. In the evaporator, liquid ammonia evaporates and diffuses into hydrogen gas, which is the gas used to balance the pressure of the refrigeration system.

3.6. Theoretical calculation of moisture removal process

3-4: The process of cooling the drying agent to the dew point temperature. Point (3) is the state of the air after passing through the drying chamber and being completely recirculated, point (4) is the state of the air in the evaporator, at the beginning of the moisture reduction.

4-1: The process of dehumidification. Point (1) is the state of the air at the end of the dehumidification stage.

1-2: The process of heating the drying agent to the drying temperature. Point (2) is the state of the hot air before entering the drying chamber.

2-3: The drying process. The drying agent with low humidity is blown into the drying chamber when the difference in water vapor is large, causing the process of evaporation of water into the drying agent and condensation of moisture in the evaporator.

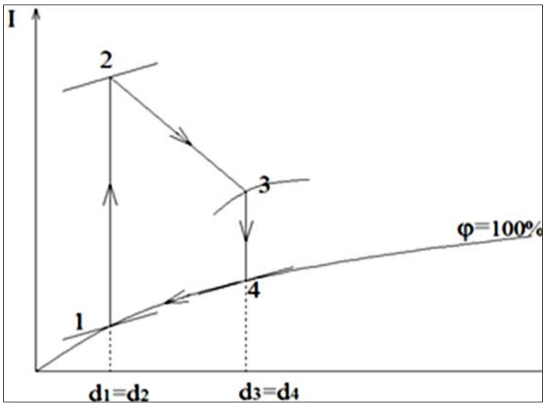

Figure 6 Representation of the moisture separation and air heating process on the i - d graph

3.6.1. Determination of evaporation moisture

Product weight in 1 batch.

$$G_1 = \frac{G_2.(100 - w_2)}{100 - w_1} \text{ (kg/batch)} \qquad (2.13)$$

Amount of moisture evaporated in a batch.

$$W = G_1 \frac{\omega_1 - \omega_2}{100 - \omega_2} \text{ (kg/batch)} \qquad (2.14)$$

We choose the dehumidification time τ = (h) according to the calculation results above. The amount of moisture evaporated in 1 hour

$$W_h = \frac{W}{\tau} \text{ (kg/h)} \qquad (2.15)$$

3.6.2. Amount of dry air required to evaporate 1 kg of moisture

$$l_0 = \frac{1}{d_3 - d_2}(kgkk / kg_a) \qquad (2.16)$$

Circulating dry air flow during drying

$L_{lt} = W.l_0$ (kg_{kk}/batch) (2.17)

3.6.3. Heat supplied by the resistor to evaporate 1 kg of moisture

$$q_{lt} = \frac{I_2 - I_1}{d_3 - d_2} \text{ (kJ/kg}_a) \qquad (2.18)$$

Heating the air after cooling and dehumidification

$Q_{lt} = W.q_{lt}$ (kJ) (2.19)

Heating the air after cooling and dehumidification

$$Q_{0\,lt} = \frac{Q_{lt}}{\tau}(kW) \qquad (2.20)$$

Condensation moisture:

$\Delta d_{lt} = d_3 - d_2$ (kg_a) (2.21)

3.6.4. Amount of heat obtained from condensing 1 kg of moisture

$q_{ll\,lt} = l_0.(I_3 - I_1)$ (J/kg_a) (2.22)

Amount of heat the evaporator receives

$Q_{ll\,lt} = W.q_{ll\,lt}$ (kJ) (2.23)

List of symbols and abbreviations

Symbol	Significance	Symbol	Significance
P_h	Saturated vapor pressure	$G_{â}$	Moisture removed
P_k	Condensing pressure	φ	Relative humidity
Q_0	Cooling capacity	φ_2	Relative humidity after heating
Q_k	Heat capacity	$t_{ư}$	Wet bulb temperature
t_1	Air temperature leaving the evaporator	t_{kh}	Dry bulb temperature
t_2	Heated air temperature	t_{tb}	Average temperature
t_k	Refrigerant condensing temperature	t_{bm}	Evaporator surface temperature
t_0	Refrigerant evaporation temperature	η	Dehumidification performance
t_{mts}	Drying environment temperature	τ	Time (minutes)
I	Wet air enthalpy	ω	Air speed (TNS)
D	Vapor content	VLS	Drying material
G,L	Drying agent flow rate		

4. Conclusions

To dehumidify the air, the air must be cooled to the dew point and then cooled further to remove the moisture in the air in the form of condensate. However, the dehumidification efficiency also depends on the structure, surface contact area of the device, cooling temperature, air movement velocity, inlet humidity, blade pitch and surface roughness of the device.

The cooling method remains a widely utilized and effective approach for moisture removal from air, primarily due to its straightforward implementation and reliable results. This study has highlighted the significant role that factors such as cooling temperature, relative humidity, and system design play in determining the efficiency of this dehumidification technique. It was found that optimizing these parameters can lead to substantial improvements in condensation rates and energy efficiency, thereby enhancing the overall performance of cooling-based moisture removal systems.

Despite its advantages, the cooling method has limitations, particularly in terms of high energy consumption in hot and humid climates. Addressing these challenges requires the integration of advanced technologies, such as innovative heat exchangers, alternative refrigerants, and adaptive control strategies, to make the process more energy-efficient and environmentally sustainable. Future research should focus on the development of these technologies to reduce operational costs and minimize the carbon footprint of dehumidification systems.

Overall, this study contributes to the understanding of the principles governing the cooling method for moisture removal and provides a foundation for future advancements in dehumidification techniques. By improving energy efficiency and reducing environmental impact, these innovations will be critical in meeting the growing demand for sustainable climate control solutions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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