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Research Article

Advancements and Performance of Evaporative Cooling Technologies: Applications, Benefits, and Future Prospects

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ABSTRACT

Evaporative cooling is a widely adopted technology for various applications, including industrial processes, HVAC systems, building cooling, and microclimate regulation. It is known for its cost-effectiveness, energy efficiency, and environmental friendliness compared to conventional refrigerants. With buildings accounting for a significant portion of global energy use, enhancing cooling technology efficiency is critical. This review explores recent advancements in evaporative cooling technologies, particularly those involving desiccants, membranes, and hybrid systems, such as air-mediated indirect evaporative cooling (AMIEC) and water-mediated indirect evaporative cooling (WMIEC). These innovations address traditional challenges like maintenance, efficiency fluctuations, and ambient condition dependencies, while offering sustainable alternatives to ozone-depleting refrigerants. The review delves into the principles and classifications of evaporative cooling, detailing both direct and indirect methods using air and water as cooling media. Factors influencing the efficiency and cost of these systems, such as materials for water evaporation interfaces and design improvements, are discussed. Enhanced evaporative cooling techniques, including desiccant sorption and membrane-assisted cooling, are highlighted for their potential to improve performance in humid environments. Furthermore, the review examines the performance metrics of evaporative coolers, such as cooling capacity, energy efficiency ratios (EER), and effectiveness. Case studies and performance analyses of modified evaporative coolers demonstrate significant energy savings and increased efficiency. Despite challenges like high humidity sensitivity and maintenance needs, ongoing research and development are paving the way for more robust and efficient designs. The integration of evaporative cooling with other technologies, such as vapor compression and solar energy, holds promise for future advancements. In conclusion, evaporative cooling represents a sustainable and efficient alternative to traditional cooling methods, with significant potential for reducing global energy consumption and environmental impact. Continued innovation and addressing current limitations will enhance its applicability and effectiveness, positioning evaporative cooling as a key technology in the future of energy-efficient cooling solutions.

1. INTRODUCTION

Evaporative cooling has widespread applications in industrial processes, HVAC systems, building cooling, and microclimate regulation [1]–[4]. It's cost-effective, energy-efficient, and environmentally friendly, especially compared to

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conventional refrigerants like CFCs [5]. With buildings consuming a significant portion of global energy, the importance of efficient cooling technologies cannot be overstated[6] .In microclimate cooling, evaporative cooling offers advantages such as greater cooling capacity and portability compared to other methods like chilled liquid garments or phase change materials [7]. Researchers are focusing on developing compact, flexible, and lightweight systems to meet diverse needs, from household cooling to astronaut life support [8]. Recent advancements in evaporative cooling, particularly those leveraging desiccants, membranes, or their combination, are at the forefront [9]. Techniques like air-mediated indirect evaporative cooling (AMIEC) and water-mediated indirect evaporative cooling (WMIEC) showcase efficiency and versatility across various applications [10]. The review addresses environmental concerns by highlighting the sustainability of evaporative cooling technologies, which steer clear of ozone-depleting refrigerants. It also acknowledges challenges like maintenance needs, efficiency fluctuations based on ambient conditions, and technological constraints, pointing towards areas for future research and development. Ultimately, the aim is to provide a comprehensive resource on recent innovations in evaporative cooling, discussing applications, benefits, challenges, and future prospects.

2. EVAPORATIVE COOLING TECHNOLOGIES

Evaporative cooling relies on the principle that water absorbs heat during evaporation, lowering the system's temperature. This method offers benefits such as energy and cost savings, elimination of CFCs, reduction of CO_2 and other harmful emissions, improved indoor air quality, and enhanced life cycle cost effectiveness.

The process involves two fluid streams: water (or steam) and air, which can act as either the cooling medium or a supplement. Depending on the cooling medium, evaporative cooling is classified into air cooling or water cooling.

Air Cooling: Here, air serves as the cooling medium and water as the supplementary medium. Water evaporates, cooling the air, which is then used to cool the target object or space. This method is common in HVAC systems, providing cooled and humidified air within a comfortable thermal zone.

Water Cooling: In this method, water is cooled by evaporating part of it, and the cooled water is then used as the cooling medium. This process is exemplified by cooling towers, where hot water is sprayed onto pads while dry air is blown to facilitate evaporation.

Evaporative cooling is further divided into direct and indirect methods, depending on whether the cooling medium directly contacts the supplementary medium.

Direct and Indirect Evaporative Cooling In direct evaporative cooling, cooling occurs as water directly interacts with air. For instance, in a cooling tower, air acts as the supplementary medium while water evaporates, cooling the air which is then used as the cooling medium. In indirect evaporative cooling, water evaporates in a separate compartment, and the resulting cool air is used as the cooling medium in air systems or as the supplementary medium in water systems. Evaporative cooling can also be ambient or enhanced: Ambient Evaporative Cooling: Utilizes natural air as the cooling or supplementary medium. Enhanced Evaporative Cooling: Involves pre-processing ambient air to reduce moisture before using it as the cooling or supplementary medium. This processed air then undergoes evaporation, providing cooled and humidified air.

3. FACTORS AFFECTING AMDEC EFFICIENCY AND COST

The efficiency and cost of an Ambient and Mechanically Driven Evaporative Cooling (AMDEC) process are influenced by the design and materials of the water evaporation interface. Recent advancements include using materials with high water-absorbing capacities, such as porous metal, cellulose, organic polymer, and ceramic pads, to enhance water distribution and efficiency [11][12]. These materials need to have excellent water absorption, thermodynamic properties, corrosion resistance, fire resistance, and antifouling capabilities [13]. While AMDEC is cost-effective, environmentally friendly, and scalable, its efficiency is highly dependent on ambient temperature and humidity [14]–[16]. High humidity can raise the chilled air's relative humidity to 60-80%, causing rust and health issues from water-borne bacteria, making AMDEC most suitable for dry, hot climates with ambient humidity below 30%. Mineral and bacterial buildup requires regular maintenance, and the system's complex piping for water recirculation can lead to water wastage and equipment damage if leaks occur.

4. AIR-MEDIATED COOLING

n evaporative cooling, air-mediated cooling uses air as the primary cooling medium along with water [17]. The air is cooled by evaporating water and then provides direct cooling effects [18]. This method includes two basic types, and each type is divided into three methods of evaporative cooling, as shown in the diagram in Figure (1).

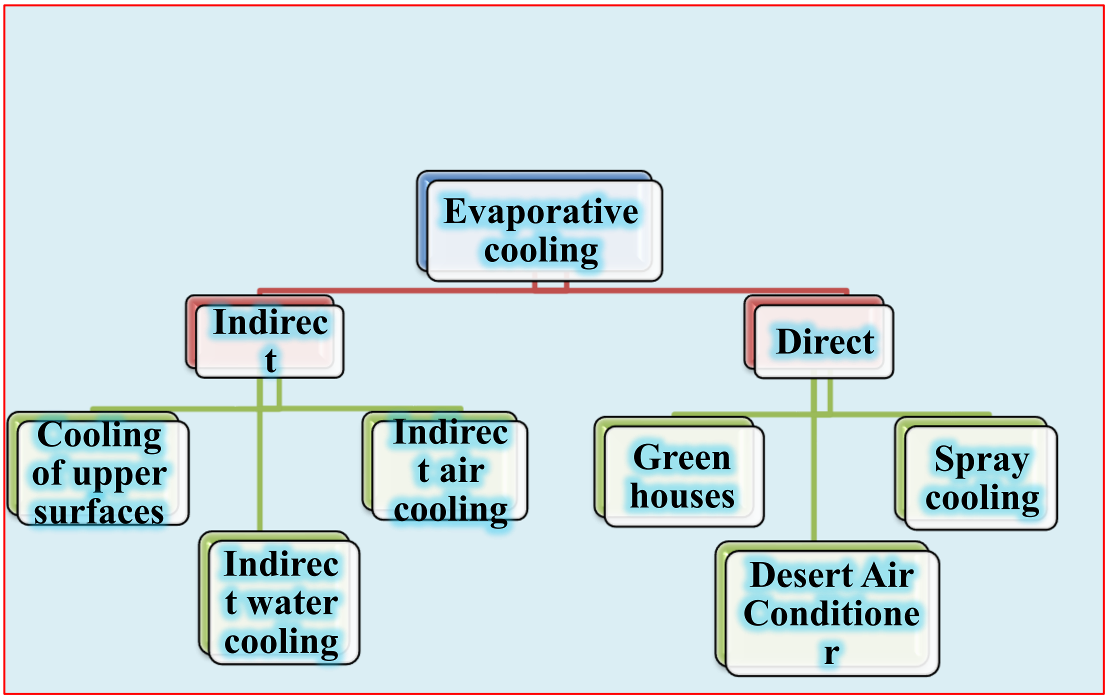

Fig. 1. The diagram shows the types of evaporative cooling.

4.1 Air-Mediated Direct Evaporative Cooling (AMDEC)

AMDEC includes direct air exposure. It is a simple and traditional method, new for good and hot climates [19]. The air passes through the wet pad or drinking water, cooling the air to about 20 °C (6.7 °C) and humidifying it [20]. An example of this is the direct cooler using a honeycomb pillow, as water flows from the top to the bottom of the honeycomb pillow and moisturizes it, cooling and humidifying the air flowing through it as shown in Figure (2).

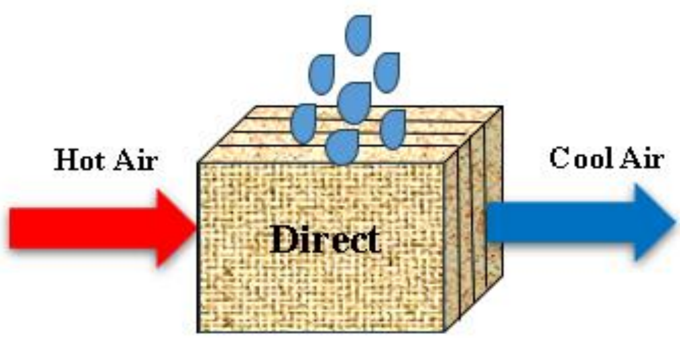

Fig. 2. The diagram Direct evaporative cooling.

4.2 Air-Mediated Indirect Evaporative Cooling (AMIEC)

Proposed by Dr. Willi Elfert in 1903, AMIEC uses two separate air streams. The primary air stream, which acts as a cooling medium, is isolated from the water side [21]. A secondary air stream passes over the water to promote evaporation [22]. Heat is transferred between the primary and secondary air streams via the heat exchange interface as shown in Figure 3, which prevents moisture from entering the primary stream and produces cooled air with low humidity [23]-[25]. Although the cooling efficiency of AMEC is generally lower than that of AMDEC due to an additional heat transfer step, it offers significant advantages:

It provides cool, dry air and prevents rust. Reduces contamination caused by water-borne bacteria.

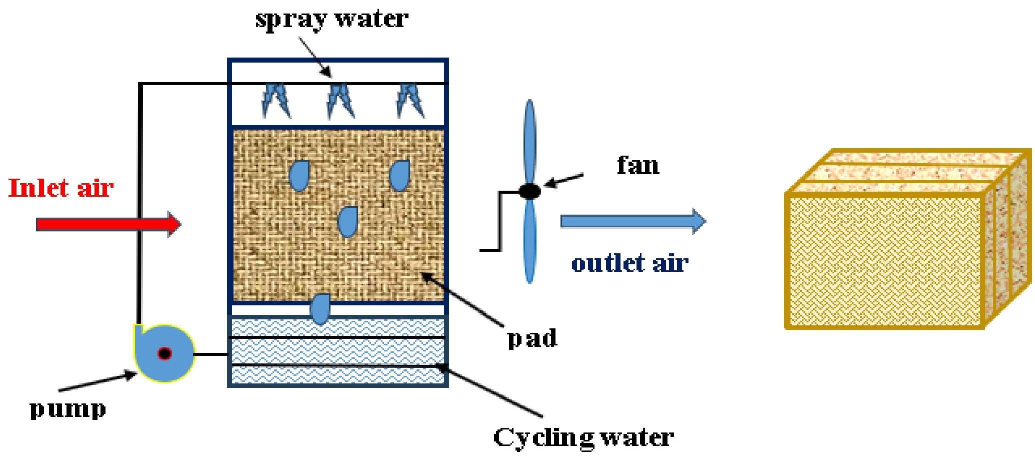

Fig. 3. example of AMDEC and its honeycomb parking material.

Various AMIEC designs improve water evaporation and heat transfer, using materials such as aluminum and ceramic for the exchanger elements [26]. Common designs include tube and plate AMIEC configurations as shown in Figure (4,a) and (4,b). Multistage AMIEC systems, such as the Maisotsenko cycle, enhance cooling efficiency by achieving lower initial air temperatures. AMEC has also been incorporated into hybrid systems, combining with technologies such as AMDEC and vapor compression to improve performance.

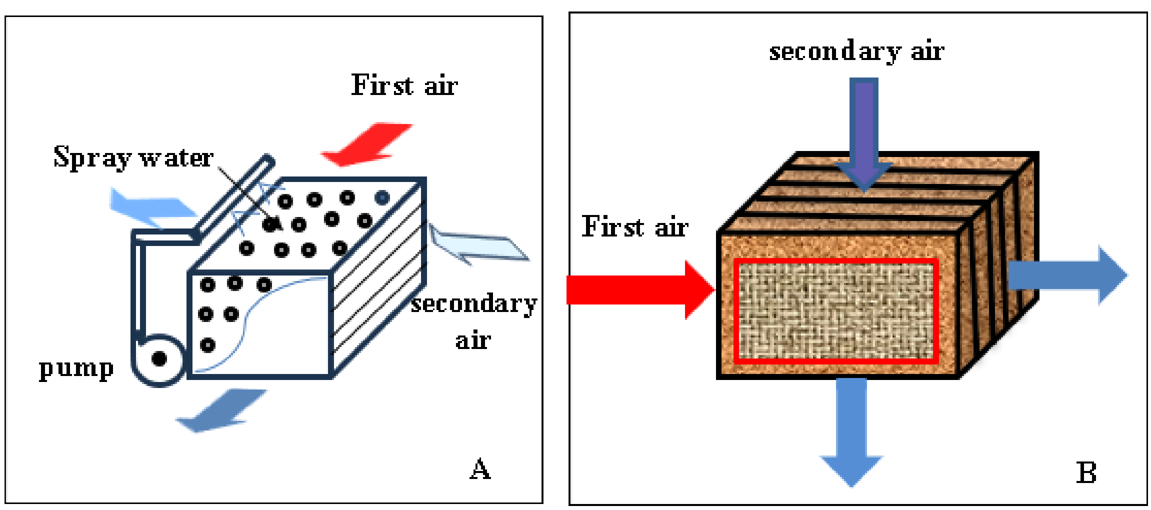

Fig .4. a.b. Tubular and plate type of AMIEC.

4.3 Water-Mediated Evaporative Cooling

Water-mediated evaporative cooling uses water as the primary cooling medium, complemented by air[17]–[19]. Excess water evaporates upon contact with dry air, cooling the remaining water, which is then used for cooling purposes[20]. Similar to air-mediated cooling, water-mediated evaporative cooling is divided into:

1. Water-Mediated Direct Evaporative Cooling: Water directly contacts air, evaporating to cool the remaining water.
2. Water-Mediated Indirect Evaporative Cooling: Water evaporates in a separate compartment, cooling the water without direct contact with the air.

4.4 Water-Mediated Direct Evaporative Cooling

A common example of water-mediated direct evaporative cooling is a cooling tower, used in HVAC systems and industrial processes to cool recycled water[21]. In a cooling tower, hot water is sprayed from the top, creating a fine mist with a large surface area for evaporation [22]. Ambient air is blown upward from the bottom, carrying the evaporated water [23]. The evaporation process absorbs latent heat, cooling the remaining water[24]. This chilled water can then be used in refrigeration systems or recycled for cooling in buildings or industrial facilities[25] .While effective, this method has drawbacks such as potential contamination of the water by airborne dust and bacteria, mineral deposition on tower and pipe surfaces, as well as issues related to the size and noise of cooling towers.

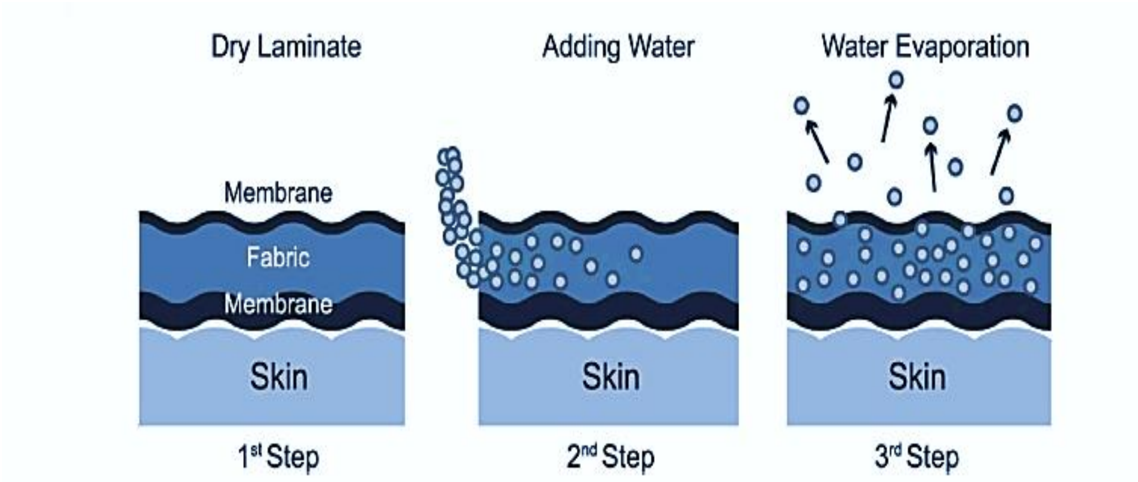

Fig.5.schematic diagrams of three-layer laminate and the principle of water evaporation from the reservoir[26].

4.5 Water-Mediated Indirect Evaporative Cooling: Multi-Layer Membrane

In water-mediated indirect evaporative cooling (WMIEC), water does not directly contact air[27]. An example is the multi-layer membrane evaporative cooling garment designed for personal cooling[28]. This garment, developed by Roth Maier et al., consists of a three-layer laminate: two waterproof, vapor-permeable hydrophobic membranes with a hydrophilic fabric layer in between[29]. Water absorbed by the hydrophilic fabric evaporates by absorbing body heat, and the vapor escapes through the top membrane, providing cooling[30] .The membranes are made of polyether-ester, allowing water vapor diffusion driven by the difference in vapor pressure between skin temperature and ambient air[31] . Water serves as the cooling medium, and ambient air is the complementary medium.
Limitations of this design include:

- Cooling capacity is limited by the water content in the fabric.
- Adding water during use can be inconvenient.
- Effectiveness depends on ambient temperature and humidity.
- Cannot be used under impermeable personal protective clothing (PPC), which blocks evaporation.

4.6 Enhanced Evaporative Cooling

Enhanced evaporative cooling improves efficiency by pre-drying (dehumidifying) the air before use[32]. This method is especially beneficial in humid conditions, where direct evaporative cooling is less effective [33]. In enhanced systems, the air whether it is the cooling medium or the complementary medium is pre-dried, enhancing cooling efficiency[34]. This is crucial in environments requiring a low dew point, such as supermarkets, museums, and indoor pools, to prevent humidity-related damage[35]. It is also vital in settings requiring high air quality, like hospitals, laboratories, and pharmaceutical production facilities [36]. Desiccant sorption is the most common technology for air dehumidification in these systems[27]. Membranes can also be used, either alone or with desiccants, to pre-dry the air, improving cooling performance and maintaining optimal air quality.

4.7 Desiccant cooling

Desiccant cooling, or desiccant-enhanced evaporative cooling, is an emerging technology in sustainable HVAC systems [17]. Dryers, which can be natural or artificial, absorb water vapor by exploiting differences in partial vapor pressure between the surface of the dryer and the surrounding air [18]. They are classified into liquid and solid desiccants, both of which are used in desiccant refrigeration systems. Figure (6) shows the dryer’s operating mechanism and the stages of drying and cooling the air into the room.

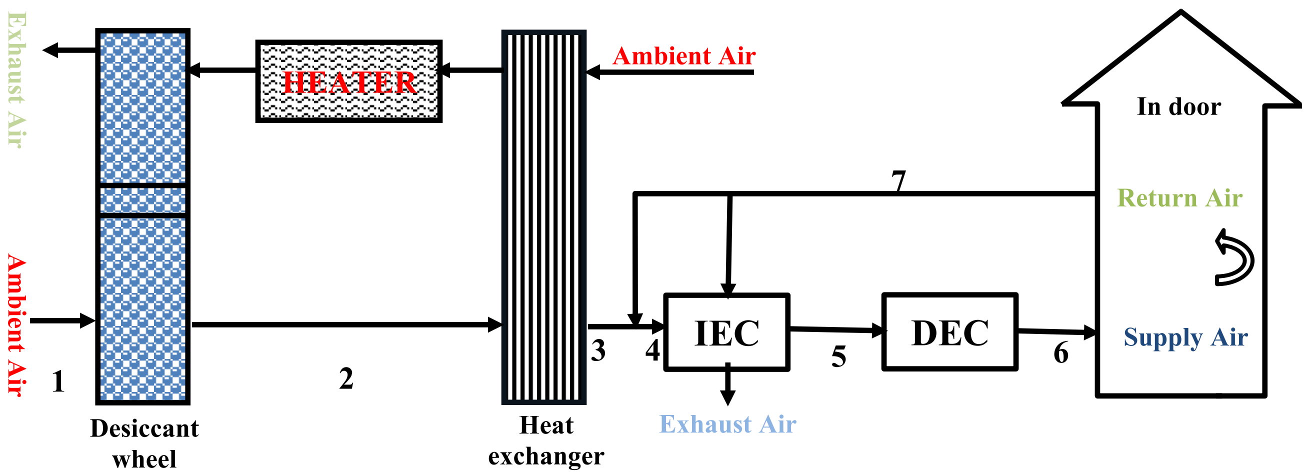

Fig. 6. Schematic of solid desiccant and evaporative cooling systems.

The dried material is the substance that absorbs water droplets present in humid air through the process of absorption [18]. The process of removing moisture and renewing cooled air is one of the most important modern developments that has engaged researchers in reducing the humidity of direct desert cooling and providing suitable comfort conditions for homes [19]. Dried materials can be solid or liquid [20]. Evaporative cooling units can operate with high coefficient of performance (COP) in dry climatic conditions, but due to air saturation in humid climates, the efficiency of these cooling units decreases significantly [11]. By removing moisture from humid air, these cooling units can operate efficiently[22]. Dehumidifiers are composed of some dried materials such as silica gel, lithium chloride, lithium bromide, activated ammonia, and natural zeolite[13]. Evaporative cooling systems with dehumidifiers lead to a significant reduction in electricity consumption compared to traditional units, as well as reducing the number of hours of discomfort inside the conditioned space[24]. The dehumidifier has a high capacity to absorb moisture from 50% to 200% of its dry weight[35]. To reactivate the dried material, it can be reactivated at temperatures ranging from 50°C to 120°C [36]. There are eight main factors that affect the performance of moisture dryers, which are (air humidity, air temperature, air velocity through the dryer, dryer activation temperature, amount of dryer used for reactivation, air currents, and dryer absorption properties).

4.8 SILICA GEL (SIO2)

is one of the most common dried materials. It is a form of silicon dioxide (SiO_2), a natural mineral that operates at temperatures below freezing and beyond the boiling point of water but performs best at room temperatures (12.1-32.2°C) and high humidity (60-90%). The performance of silica gel desiccant begins to decline at temperatures above approximately 37.7°C but continues to work until around 104.3°C, reducing the relative humidity in the space to approximately 40% at any temperature within its range until saturation [31]. Silica gel can absorb up to 40% of its weight in moisture. The diagram illustrates the type of dried granules used in the system [32]. Dried silica gel is not chemically inert and has the ability to change colour to indicate the actual moisture content[33]. It is dark blue when dry, turns purple as moisture concentration increases, and becomes pink when fully saturated, indicating it needs to be dried or replacement.

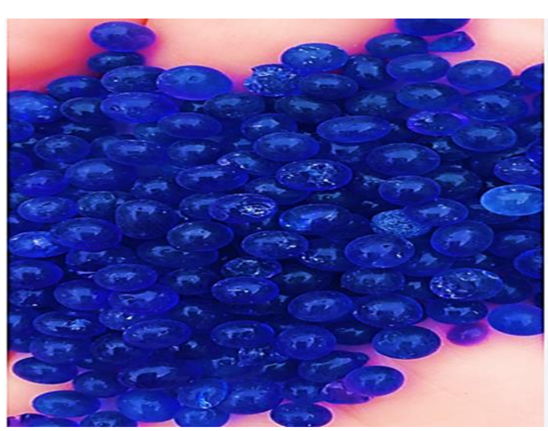

Fig.7. represents dried silica gel granules.

5. ADVANTAGES AND DISADVANTAGES OF SOLID DESICCANTS:

The main goal of using desiccant materials is to reduce undesired humidity. Therefore, the primary motivation for using dried silica gel granules lies in their advantages. Additionally, desiccant materials have disadvantages summarized in Table (I) outlining the main benefits and drawbacks as follows

TABLE. I. ADVANTAGES AND DISADVANTAGES OF SOLID DESICCANT MATERIALS.

No.	**Disadvantages of deride material**	**Advantages of desiccant materials**
1	**The ability of the dryer to absorb moisture decreases when the dried materials reach the saturation stage.**	**Solid desiccant has a higher rate of absorption of water moisture than liquid desiccant, because its surface area is much larger than its weight due to its porous nature.**
2	**Solid dryer granules need drying processes and this can be achieved using solar energy and electric heater.**	**It has a simpler structure and no risks of chemical reactions compared to liquid desiccant (water-soluble desiccant).**
3	**The ability of silica granule dryers to absorb moisture decreases if the saturation limit is reached.**	**The process of removing moisture from the air occurs through the strong water vapor attraction of the solid desiccant material due to the water vapor pressure difference between the desiccant surface and the air.**
4	**Using a rotary dryer to absorb moisture consumes some energy.**	**Using dehumidifiers as static pads or solutions in an evaporative cooling system reduces energy consumption.**
5	**The lack of granules with diameters exceeding 10 mm limits the use of solid desiccant.**	**Economically, it is considered inexpensive and available. It also reduces the use of high-cost compression refrigeration systems and contributes to reducing gas emissions that cause an impact on the ozone layer and thus global warming.**
6	**It is unable to absorb pollutants and toxins in the air.**	**Its use enables us to effectively control air humidity and maintain the air quality level.**

6. MEMBRANE-ASSISTED LIQUID DESICCANT COOLING

Membrane-assisted liquid desiccant cooling prevents cross-contamination by desiccant droplets and offers benefits like modularity, scalability, and enhanced drying efficiency [24]–[26]. Prototypes using porous membranes (0.03 to 1.00 µm) have been developed for HVAC systems. Abdel-Salam et al. introduced a system with two liquid-to-air membrane energy exchangers acting as the dehumidifier and regenerator[27]. The process involves:

1. Heat exchange between the cold, diluted desiccant from the dehumidifier and the hot, concentrated desiccant from the regenerator.
2. Heating the desiccant to evaporation temperature, allowing water vapor to escape through membrane pores.
3. Chilling the regenerated desiccant, which then dehumidifies the air feed, producing dry, chilled air.
4. Heating the diluted desiccant before it undergoes regeneration, with a heat exchanger transferring heat between the hot and cold desiccant solutions, enhancing system efficiency.

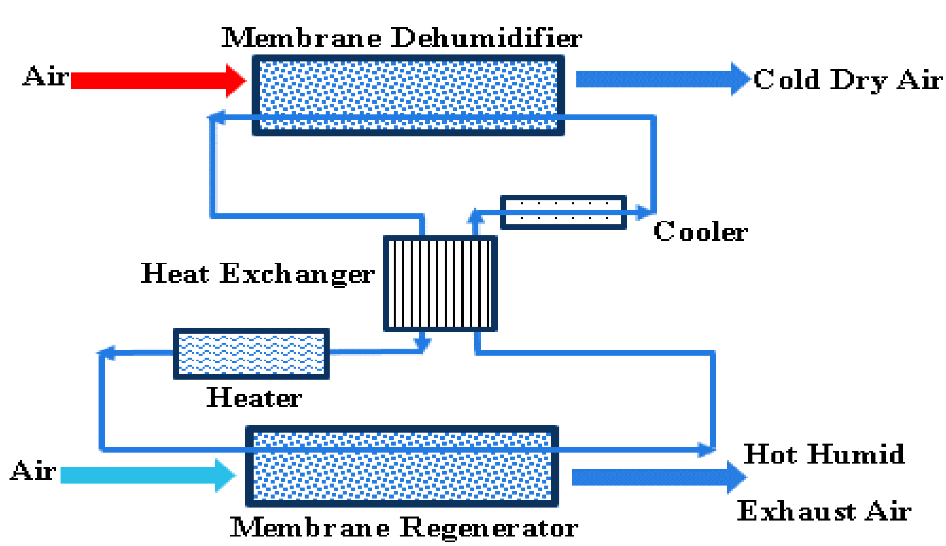

Fig.8.schematic diagram of membrane liquid desiccant air conditioning system.

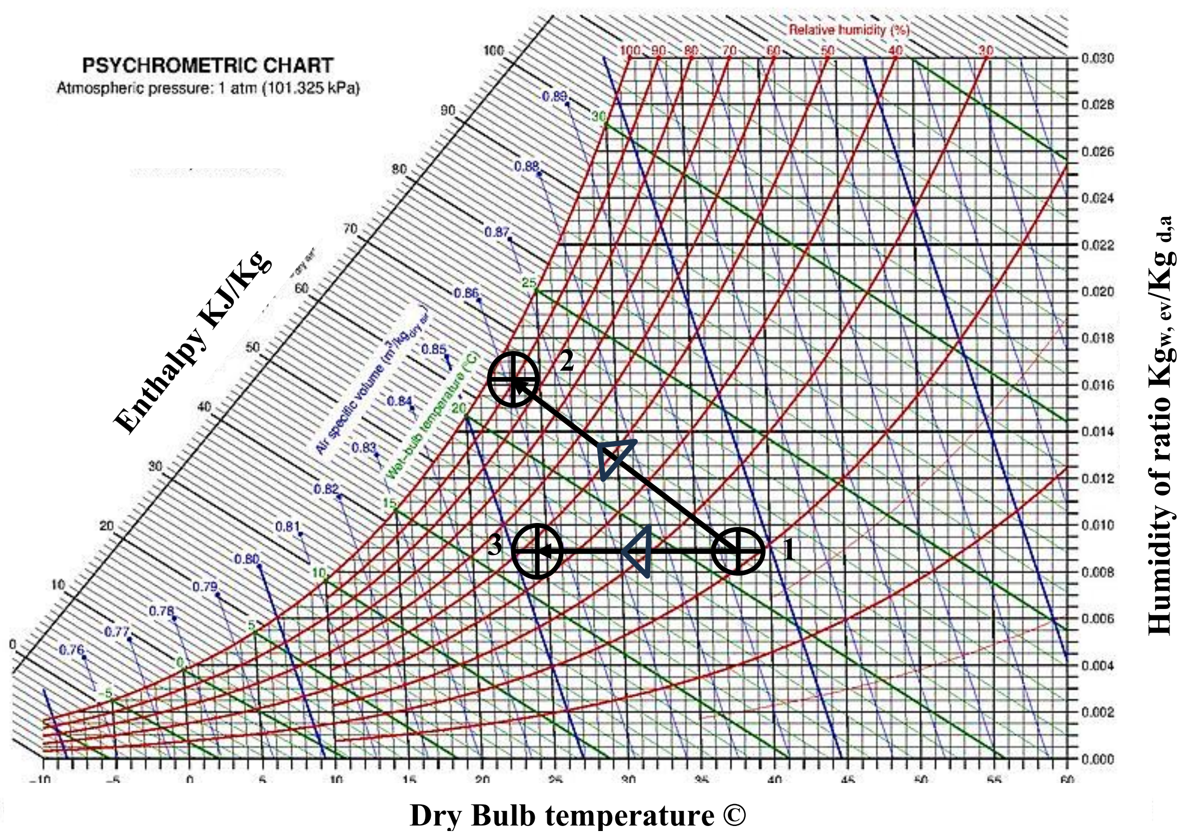

Fig. 9. psychometric of direct and indirect evaporative cooling.

7. OVERVIEW OF SOLID DESICCANT DEHUMIDIFICATION

Solid desiccant dehumidification is a key method for controlling humidity in air-conditioning systems, offering advantages such as higher water adsorption rates, simpler structures, and lower carry-over risk compared to liquid desiccants [28] [29]. The process involves removing moisture from the air using desiccant materials with strong water vapor attraction properties [20] [21]. The efficiency of this process is driven by the water vapor pressure differential between the desiccant surface and the air[32].As desiccant materials become saturated, their sorption capacity declines, necessitating a regeneration process, typically using thermal energy [32]–[34]. Regeneration can be achieved through solar energy, electrical heaters, electro-osmotic processes, or waste heat [35]. Research has focused on improving water adsorption capacity and reducing regeneration temperatures. Advances in solid desiccant materials include composite desiccants, nanoporous inorganic materials, and polymeric desiccants. Optimizing performance involves selecting appropriate host matrices and salts for composite desiccants and balancing regeneration and adsorption capacities for nanoporous inorganic materials.

7.1 EVAPORATIVE COOLING

Evaporative cooling operates in two modes: Direct Evaporative Cooling (DEC) and Indirect Evaporative Cooling (IEC).

- DEC: Water is sprayed directly into the process air stream, cooling it by increasing moisture content. It is efficient in dry climates.
- IEC: Uses a separate secondary air stream, cooled evaporatively, to cool the primary air inside a heat exchanger. It reduces enthalpy without adding moisture, making it suitable for humid climates.

IEC typically involves multiple chambers separated by heat conductor plates. Water sprayed into the secondary air stream cools it, and this cooled air transfers heat from the primary air in an adjacent chamber. The primary air is then used for space cooling, while the cooled secondary air is released.
Effectiveness:

- DEC: ~90% effectiveness

- IEC: 70-80% effectiveness
- Both are most effective when the ambient wet bulb temperature is below 25°C, achieving a COP of up to 5 in dry climates.

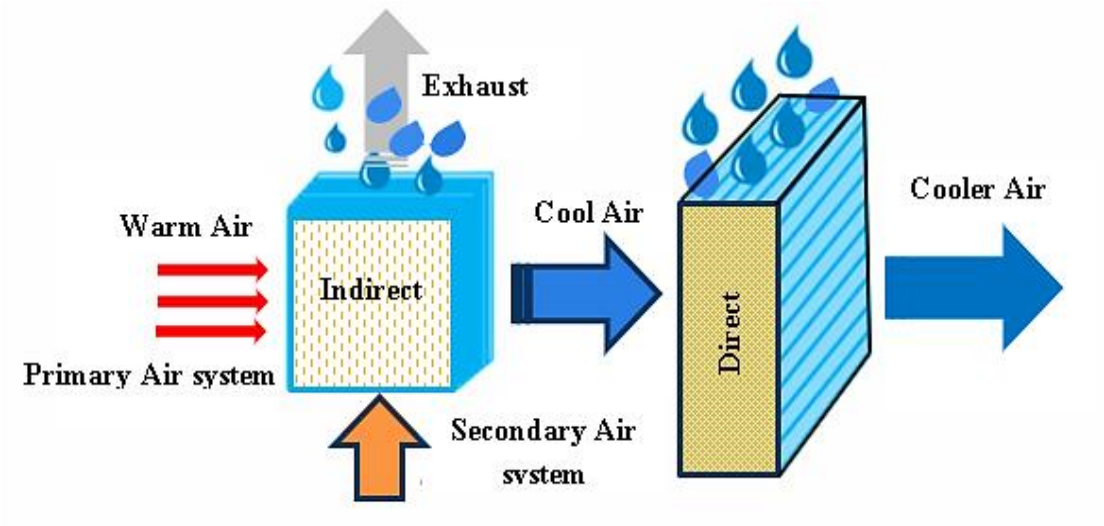

Fig. 10. shows the two-stage evaporative cooling mechanism

7.2 CHALLENGES

- Reduced effectiveness in humid climates due to near air saturation.
- Incorporating desiccant dehumidifiers can improve effectiveness by removing moisture from the processed air, forming a desiccant cooling system.

○ **Modified Evaporative Cooler**

Two-Stage System:

- Concept: Combines direct and indirect cooling to enhance efficiency.
- Stages:
  1. First Stage: Air is pre-cooled using a heat exchanger by evaporating moisture.
  2. Second Stage: Pre-cooled air passes through soaked pads for further cooling, adding less moisture and improving thermal comfort.

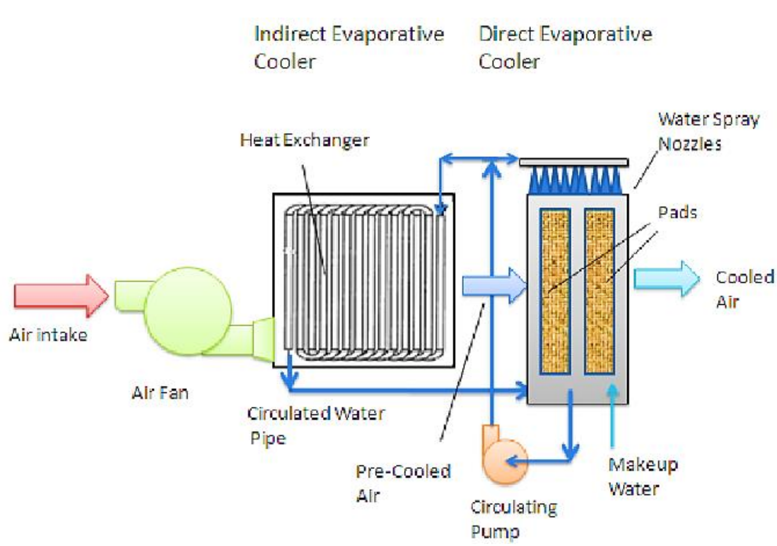

Fig. 11. indirect-direct evaporative cooling systems[66].

Energy Efficiency: Reduces energy consumption by 60-75% compared to conventional systems.

Performance Analysis:

- Kulkarni and Rajput: In Bhopal, India, found that effectiveness ranged from 0.95 to 0.82 for indirect cooling, and combined stages achieved 121-107% saturation efficiency, with cooling capacities of 5.06 to 20.50 kW.

- Watt: Analyzed various evaporative cooling systems and their principles.
- Maclaine-Cross and Banks: Developed a model showing high performance for regenerative evaporative cooling units.
- Yellott and Gamero: Found that indirect evaporative coolers can be used in most climates.

o Modern Designs:
- High-Performance Media: Incorporate media with low-velocity air, achieving up to 93% effectiveness.
- Fan Power: Modified coolers require more fan power due to air splitting.
- Research and Development:
- Local Fibers: Al-Sulaiman found jute pads had the highest efficiency at 62.2%.
- Heat and Mass Transfer Models: Alonso et al. created models for designing optimized coolers.
- Roof Heating Load: Al-Nimr et al. improved cooler performance by reducing roof heating load.

o Studies and Comparisons:
- Jain and Hindoliya: Developed a regenerative cooler with a water-to-air heat exchanger, increasing COP and efficiency by 20-25%.
- Preference: Indirect coolers preferred for low humidity requirements.

o Advancements:
- Ongoing development with key steps outlined for improving technology.

o Performance Index of Evaporative Coolers

Cooling Capacity (Q): $Q=V\times\Delta a\times Cpa\times(Ti-To)$
- Q: Cooling capacity
- V: Volume flow rate
- Δa: Air density change
- Cpa: Specific heat capacity of air
- Ti: Inlet air temperature
- To: Outlet air temperature

o Desiccant Evaporative Cooling:
- Total Cooling Load: Includes both sensible and latent cooling.

o Energy Efficiency Ratio (EER): EER=Q/W
- Win: Input energy to the cooler

o Effectiveness:
- Direct Evaporative Cooling Systems: Temperature effectiveness between 70% to 95%.
- Indirect Evaporative Cooling Systems (IEC): Cooling effectiveness ranges from 40% to 60%.
- Specific Figures:
- Indirect evaporative coolers: 70-80%
- Direct evaporative coolers: 90%

o Special Note:
- Counter indirect evaporative coolers can achieve dew point effectiveness above 100%, cooling air below its dew point temperature.

o Wet Bulb Effectiveness:
- Depicted for desiccant-based evaporative cooling systems in Fig(10).

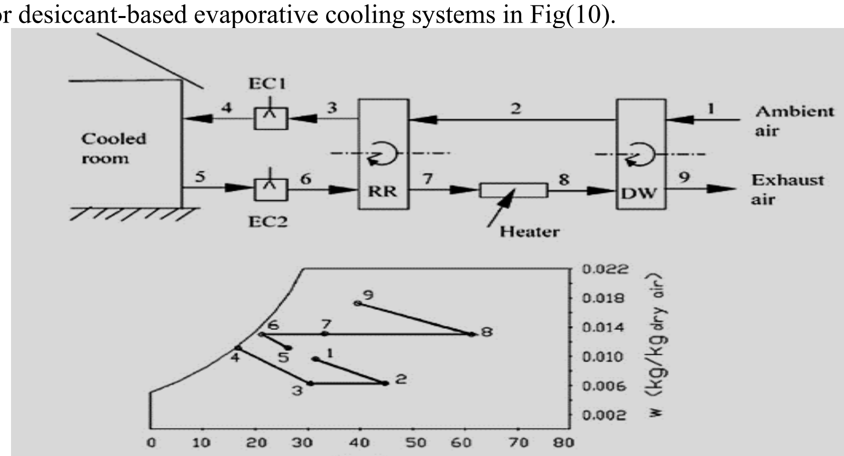

Fig. 12.A simple schematic of experimental desiccant cooling system in ventilation mode, and its psychometric chart representation for a typical operation[17].

8. CONCLUSION

Evaporative cooling represents a highly efficient, cost-effective, and environmentally friendly alternative to traditional cooling methods, especially in the context of global energy consumption and environmental impact. Its applications span from industrial processes to personal cooling systems, highlighting its versatility and potential for significant energy savings.

Recent advancements in evaporative cooling technologies, particularly the development of desiccant-enhanced systems, indirect cooling methods, and novel materials for evaporation interfaces, have addressed many of the traditional limitations such as efficiency fluctuations and maintenance requirements. These innovations have expanded the applicability of evaporative cooling to a wider range of climates and conditions, offering dry, low-humidity cooling options even in humid environments.

Air-mediated and water-mediated evaporative cooling systems, both direct and indirect, provide flexible solutions for various cooling needs. Enhanced evaporative cooling, using desiccants or membranes, further improves efficiency by pre-drying the air, making it suitable for high-demand environments like hospitals, museums, and supermarkets. This not only reduces energy consumption but also maintains optimal indoor air quality and prevents humidity-related damage.

Despite the challenges such as high humidity sensitivity, mineral and bacterial buildup, and complex system maintenance, ongoing research and development are paving the way for more robust and efficient designs. The integration of these systems with other technologies, like vapor compression and solar energy, holds promise for future advancements.

In conclusion, evaporative cooling stands out as a sustainable and efficient cooling technology with significant potential for future development. By continuing to address its limitations and expanding its applications, evaporative cooling can play a crucial role in reducing global energy consumption and mitigating the environmental impact of cooling systems.

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Conflicts of Interest:

The authors declare that they have no conflicts of interest in relation to this work.

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