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Next-generation HVAC: Prospects for and limitations of desiccant and membrane-based dehumidification and cooling

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HIGHLIGHTS

- Thermodynamic principles are applied to systematically compare three technologies.
- Merits and limits of standalone versus integrated designs are identified.
- Effect of climate conditions on performance and technology selection is evaluated.
- Integrated desiccant/membrane technologies outperform current state-of-the-art VCS.

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ABSTRACT

Recently, next-generation HVAC technologies have gained attention as potential alternatives to the conventional vapor-compression system (VCS) for dehumidification and cooling. Previous studies have primarily focused on analyzing a specific technology or its application to a particular climate. A comparison of these technologies is necessary to elucidate the reasons and conditions under which one technology might outperform the rest. In this study, we apply a uniform framework based on fundamental thermodynamic principles to assess and compare different HVAC technologies from an energy conversion standpoint. The thermodynamic least work of dehumidification and cooling is formally defined as a thermodynamic benchmark, while VCS performance is chosen as the industry benchmark against which other technologies, namely desiccant-based cooling system (DCS) and membrane-based cooling system (MCS), are compared. The effect of outdoor temperature and humidity on device performance is investigated, and key insights underlying the dehumidification and cooling process are elucidated. In spite of the great potential of DCS and MCS technologies, our results underscore the need for improved system-level design and integration if DCS or MCS are to compete with VCS. Our findings have significant implications for the design and operation of next-generation HVAC technologies and shed light on potential avenues to achieve higher efficiencies in dehumidification and cooling applications.

1. Introduction

Building operation consumes more than 40 percent of the total energy used in the United States [1], and building heating and cooling loads comprise the largest fraction. Demand for cooling energy is exacerbated in hot and humid climates. High humidity poses a serious limitation to the design and operation of buildings, promoting mold and dust mites and often associated with increased disease transmission. Consequently, dehumidifying air in building ventilation systems is normally a requirement to mitigate the effects of high humidity, improve indoor thermal comfort, and meet indoor design conditions.

For over a century, the vapor-compression system (VCS) has been the de facto technology of choice in heating, ventilation, and air conditioning (HVAC), especially for dehumidification and cooling. In spite of its success, research, policy, and economics all encourage change in light of its many inherent shortcomings. From an energy standpoint, the inability of the VCS system to decouple latent and sensible loads leaves condensation, an energy intensive process, as the only means for dehumidification. The heart of the VCS system lies in the refrigerant, whose chemistry has evolved in response to policy and environmental concerns. From chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), banned

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Nomenclature

Roman symbols

c_p	specific heat at constant pressure, kJ/(kg K)
COP	coefficient of performance
h	specific enthalpy, kJ/kg dry air
h_{fg}	enthalpy of vaporization, kJ/kg
$\dot{m}$	mass flow rate of dry air, kg/s
$\dot{Q}$	rate of heat transfer, kW
P	pressure, kPa
r_p	compression ratio
R_a	ideal gas constant of dry air, 0.287 kJ/(kg K)
RH	relative humidity
s	specific entropy, kJ/(K kg dry air)
$\dot{S}_{gen}$	rate of entropy generation, kW/K
T	temperature, K
$\dot{W}$	rate of work transfer, kW
$\dot{w}$	specific work transfer, kJ/kg dry air

Greek symbols

α	humidity removal fraction
η_{II}	second law efficiency
ϵ_{HX}	heat exchanger effectiveness
ϵ_S	membrane exchanger sensible effectiveness
ϵ_L	membrane exchanger latent effectiveness
ω	humidity ratio, kg moisture/kg dry air
$\tilde{\omega}$	mole fraction of vapor to air in the moist air mixture
ξ	total specific exergy, kJ/kg dry air

Subscripts

a	dry air
ad	adsorption
c	cooling
cool	cooling load
coil	cooling coil
cond	condensation
h	heating
i	stream identity
lat	latent load
p	pressure
reg	regeneration
sat	saturation
v	vapor
w	liquid water
0	environment or dead state

Abbreviations

DCS	desiccant-based cooling system
DW	desiccant wheel
IEC	indirect evaporative cooler
MCS	membrane-based cooling system
VCS	vapor-compression system

under the Montreal Protocol in 1987 [2], to hydrofluorocarbons (HFCs), such as R-134a with a global warming potential (GWP) 1430 times that of carbon dioxide (CO_2) [3], environmental concerns associated with VCS can no longer be overlooked. These concerns, coupled with potential excess greenhouse gas (GHG) emissions resulting from the inefficiencies inherent in the system, place research on future HVAC technologies at the cornerstone of any effort aimed at mitigating climate change.

The United States, Canada, and Mexico recently proposed to curb their use of HFCs by 85% between 2016–2033 [4], while several members of the European Union supported an agreement to phase out HFCs by 80% between 2016–2030 [5]. These efforts, among others, paved the way for the Kigali accord, an amendment to the Montreal Protocol signed by more than 170 countries to phase out HFCs. In response to the rising interest in the future of HVAC, Chua et al. [6] presented a review of recent HVAC innovations to achieve improved air-conditioning efficiency, while the U.S. DOE published a study shortlisting potential next-generation HVAC technologies [7,8], highlighting the potential of two technologies of interest to our study, desiccant and membrane technologies.

Desiccant technology employs desiccants, normally solid or liquid materials with a high affinity for water vapor, to separate water vapor from outdoor air and thereby decouple dehumidification from the cooling process [9]. Daou et al. [10] reviewed different configurations of the desiccant cooling system (DCS), and La et al. [11] pointed out the merits of the solid rotary DCS (known as a desiccant wheel): compactness, continuous working hours, and lower susceptibility to corrosion during operation. To analyze its potential for regeneration using low-grade heat, Angrisani et al. [12,13] experimentally investigated the effect of outdoor conditions and regeneration temperature on desiccant wheel performance. Given the promise desiccants offer for more efficient air conditioning, several configurations employing desiccant wheels, such as the combined chilled-ceiling desiccant cooling system [14], continue to be investigated in the literature.

In contrast with desiccant technology, the isothermal nature of chemical separation in membrane technology poses a unique advantage, and its incorporation in HVAC has lately been an active field of research. In recent reviews, Woods [15] and Zhang [16] provided overviews of the latest membrane developments in HVAC and a summary of potential avenues for future research, while another review by Yang et al. [17] highlighted the major advances membrane technology has made in air dehumidification. In search of membranes with the greater selectivity necessary to make this process viable, Zhang et al. [18] developed a novel membrane using a polyethersulfone (PES) support layer coupled with a polyvinylalcohol (PVA) active layer, while Bui et al. [19,20] later reported the fabrication of a robust hydrophilic PVA/LiCl composite membrane. Other studies explored boosting air-conditioning performance through incorporating membrane-based total heat recovery [21,22], enabling heat and mass exchange across air streams.

Another prominent application of membrane technology has been membrane-based liquid desiccant dehumidification, recently reviewed by Huang et al. [23] and Abdel-Salam et al. [24]. Compared to solid desiccants, liquid desiccants allow for localized dehumidification and for regeneration to occur at lower temperatures [9], while integrating them with membranes eliminates the challenge of desiccant cross-over [23]. Research in the field continues to investigate several aspects of this technology, including modeling system performance [25–27], improving system design [28], and employing renewable energy [29].

Apart from the question of which technology produces the dehumidification and cooling effect, HVAC is an energy conversion process, whose design and performance can considerably benefit from a greater thermodynamic understanding. Even many decades after the inception of VCS, for example, thermodynamic analysis aimed at improving VCS performance and efficiency continues to be relevant to this day, as evident from the works of Kumar et al. [30], Bayrakçi and Özgür [31], and a recent review by Ahamed et al. [32], to name a few. Similarly, Zhang [33] presented an