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Performance investigation on polymeric electrolyte membrane-based electrochemical air dehumidification system

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HIGHLIGHTS

- An electrolytic dehumidifier with a PEM element was investigated.
- The system could dehumidify the air streams under a low-voltage electric field.
- The energy efficiency was advantageous to other electrochemical dehumidifiers.
- Humidity decreased from 70 to 90% to less than 30% RH under a 3 V electric field.
- Energy and dehumidification efficiency was 1.5–2.0 × 10^{-2} g/(J·m^2) and 0.6–1.5 × 10^{-2} g/(s·V·m^2) respectively.

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ABSTRACT

An electrochemical air dehumidification system with polymer electrolyte membrane (PEM) was developed. The system performance under various operating conditions was investigated experimentally. A semi-empirical prediction model was also developed with multi-parameter linear regressions. Results showed that the novel system could dehumidify the air flow, with a humidity decrease from 90% (inlet) to less than 30% RH (outlet) under a 3 V electric field, which is promising as it can achieve an independent, portable and energy-efficient moisture removal. The steady-state dehumidification performance derived was 80 kg/(kW h·m^2), or 54 kg/(h·V·m^2), which were advantageous to current electrochemical dehumidifiers. Specially, this simple element has a volume of only 0.001–0.01‰ of traditional ones, which is also suitable for cascading or multilevel assembly to satisfy various requirements for commercial and industrial applications. The moisture transfer, mainly caused by the electrolysis (+), electro-osmosis (+) and back diffusion (−), increased significantly with the increases in anode-side air humidity and flow rates. When the inlet air humidity increased from 70 to 90%, the dehumidification rate increased about 1.5–2 times. However, only 30% of total power input was effectively used in current element, and the rests were lost, leading to a relatively low system COP (≈0.33). The main reason was that the back-diffusion mass transfer was found to be up to 2.3 times larger than expected, causing by the high moisture content in cathode-side layers (mainly the diffusion layer), which seriously deteriorated the system performance. Therefore, enhancing the diffusion layer performance may help to optimize the dehumidification efficiency effectively. The suggested measures include improving the structure, changing the internal surface parameters or adding microporous layers, etc.

1. Introduction

The number of air-conditioned buildings has increased rapidly worldwide over the past 20 years. The indoor humidity control is necessary and its energy consumption occupies around 10% of total energy consumption in China [1]. Humidity control is also significant for ensuring the product quality in electronic and precision manufacturing [2]. The moisture sensitivity level of production equipment and components become increasing higher with the development of manufacturing industry [3]. However, traditional air handing technology has many problems, especially for humid areas such as southern China. As dealing with sensible and latent loads simultaneously, conventional air-

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Nomenclature

A	area (m^2)
c_p	specific heat capacity (J/(kg·K))
COP	coefficient of performance (−)
D	diffusion coefficient (m^2/s)
E_w	equivalent weight of electrolyte membrane (g/mol)
E_{con}	concentration overpotential (V)
E_{act}	activation overpotential (V)
h	enthalpy (kJ/kg)
I	current (A)
$\dot{m}$	mass flow rate (kg/s)
m	weight (kg)
n_d	electro-osmotic drag coefficient (−)
Sh	Sherwood number (−)
t	temperature (°C)
q	heat flux (w)
λ	water content (−)
δ	thickness (m)
ρ_{dry}	dry density (kg/m^3)
ω	moisture content (kg/kg)
η	efficiency (−)

Subscripts

a	air
w	water
m	membrane
A	anode side
C	cathode side
ele	element
mem	membrane
diff	diffusion layer
in	inlet
out	outlet
removal	moisture removal rate
de	dehumidification

conditioning systems (AC) operate at low evaporating temperatures [4], which leads to a low coefficient of performance (COP) and a possibility of reheating the supply air. It also has other limitations such as insufficient dehumidification capacity, overuse of CFC, wet surfaces breeding mildew and bacteria, surface corrosion, electrical breakdown, etc. It is estimated that around 25% of defective industrial products was related to the humidity problems in China [5].

The humidity independent control AC systems were developed to solve this problem by dealing with the air moisture separately. Many researchers have investigated the chemical dehumidification technologies by liquid desiccant absorption [6–8] or by solid desiccant adsorption [9–11]. Though the dehumidification method could overcome some drawbacks of traditional ones, it still has practical limitations in commercial and industrial applications. As the desiccant needs to be regenerated, the system is usually complex and requires a large space [12]. Furthermore, the desiccant droplet may be carried over by the process air during the liquid desiccant dehumidification, which may cause corrosions on metal surfaces and indoor devices, and healthy issues for occupants. Recently, a membrane-based liquid desiccant system was developed to avoid there problems [13–15]. However, it seriously increased the system complexity, as well as the space.

As a space-flexible, clean and renewable-energy friendly alternative, the electrochemical dehumidification has attracted increasing interests in recent years. This kind of method could drive the moisture from humid air to process air directly with the electric field, without cooling water or absorbent/adsorbents. Therefore, the system is quite simple, requiring only the power supply instead of cooling coil and/or other regeneration components like compressors. Currently, the method includes the electro-osmotic, thermoelectric, electrodialysis dehumidification, etc. In 2010, Qi et al. developed an electro-osmotic dehumidification with artificial zeolite in a closed chamber [16]. They observed a moisture removal rate of 0.88–1.7 × 10^{-2} g/(J·m^2) [17]. In 2012, Yan et al. improved the electro-osmosis effect with solid desiccant arrays, and they achieved a mass flow rate of 2.0 × 10^{-2} g/(J·m^2) under 20 V DC voltage [18]. However, in 2014, Zhang et al. found that the surrounding air for electro-osmotic dehumidification should be over-saturated, which made it not suitable for practical air-conditioning systems [19]. In 2016, Shen et al. investigated the thermoelectric dehumidification, which utilized cool surfaces generated by Peltier effect to dehumidify. The energy efficiency derived in this research was around 0.93–2.4 × 10^{-2} g/(J·m^2) [20]. Regretfully it is a kind of cooling dehumidification [21]. Recently, Huang et al. proposed an electrodialysis dehumidifier, using 40 kV high-voltage electricity to drive air moisture move directionally, which cannot be applied in commercial or residential buildings [22].

The dehumidification with electrolytic materials, regarded as a kind of electrochemical dehumidification, is a creative and innovative technology. In 2000, Iwahara et al. developed a laboratory-scale air dehumidifier and validated its possibility under a DC voltage, using the SrCeO-based proton conducting ceramic [23]. In 2005, Onda et al. analyzed the electrolytic mass transfer inside a confined space. They found the electro-osmotic effect cannot be neglected [24]. In 2009, Sakuma et al. tested the electrolytic dehumidification by assembling a solid membrane between two closed chambers, whose energy efficiency was around 0.23 × 10^{-2} g/(J·m^2) [25]. Then, they measured the V-I characteristics and analyzed the influences of air temperature on system performance [26]. Then, Kenro et al. proposed a possible electrolytic dehumidifier with cascading membrane structures [27]. In 2010, an experimental prototype was proposed by Ryosal Technica for small-scale humidity control for instruments [28]. There are also several studies about the transport properties of water and ions through the PEM under the fuel cell conditions [29–32], and the membrane distillation with electrochemical reactions [33,34], which could be referred of this research.

The literature review indicated that this electrolytic dehumidification system could achieve an accurate, portable and energy-efficient dehumidification, which is suitable to for commercial and industrial applications. It could also be combined with the solar PV panels and other low-voltage power supply. However, previous researches only preliminarily validated its possibility within closed chambers. The coupling with air flows on both membrane sides were not considered, which made it not practical for real conditions.

Therefore, in this paper, a membrane-based electrolytic dehumidification system with air flows was developed and investigated. The membrane element was composed of a proton polymer electrolytic membrane (PEM), porous electrodes with catalytic layers on both sides, and diffusion layers on both outermost sides. Two air channels, for humid and process air stream respectively, were coupled to the PEM element. Nafion 117 was used as the electrolytic membrane. The system performance (dehumidification rate, energy efficiency, COP, mass/heat transfer rate, etc.) under various air-conditioning conditions and main influencing factors were experimentally investigated. Based on the test data, a semi-empirical model was developed with the multi-parameter linear regression method. Possible solutions to improve the system performance were also proposed.

In simple words, the novelty of this study is that: (1) a simple and compact electricity driven system for dehumidifying the air flows was firstly developed, which is advantageous for both commercial and