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Heat and mass transfer in a polymeric electrolyte membrane-based electrochemical air dehumidification system: Model development and performance analysis

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In this paper, a two-dimensional steady-state theoretical model was established, to model the internal transport phenomena in a polymeric electrolyte membrane-based (PEM-based) air dehumidification element. The influences of electrochemical reactions, activation and concentration over-potentials, and Ohmic and electro-osmotic effects were considered. The model was solved by the finite difference method with conjugate boundary conditions. So, with this model, the heat, mass and current transfer through the five layers of the element (diffusion layers, catalyst layers and a PEM) could be described theoretically, as well as the convective heat and mass exchange with adjacent airflows. Compared with the results from previous models, this model showed a much closer trend to the experimental data. The overall error was less than 15%, with an acceptable average error of 8.6%. However, greater deviations were observed under larger airflow conditions, probably due to the assumption of laminar airflow and steady-state heat conduction. Furthermore, by the performance analysis, the maximum moisture gradient was found inside the PEM, so the PEM's parameters could largely affect the system performance. With the increase in PEM water content, the dehumidification was significantly enhanced, especially when the air humidity was high. If the PEM water content was doubled, the dehumidification rate was increased by 42%. Then, decreasing the PEM thickness also improved the performance. However, the effect became minor if the thickness was less than 100 μm. It was also helpful by increasing the PEM conductivity, although the effect of this variable was relatively small. This study provided theoretical guidance for further system improvement and material preparation for PEM-based dehumidification systems.

1. Introduction

Air humidity control is a key factor for ensuring the product quality in industrial environments, especially for electronics and precision manufacturing [1,2]. Excessive air humidity can cause many problems such as mould growth, surface corrosion and electrical breakdown [3], which are more serious in humid areas. Over 70% of China's manufacturing industries are located in moist south-eastern areas, leading to the fact that about 25% of product defects are related to humidity issues. However, current dehumidification methods have some limitations in industrial applications [4]. The widely-used cooling-condensation dehumidification process requires 7–12 °C cooling water, causing many issues such as insufficient humidity control, low system efficiency and condensation-induced water droplets [5]. Recently-developed desiccant absorption systems, including the liquid desiccant absorption and desiccant wheel adsorption, could improve the dehumidification efficiency by dealing with the water vapour independently. However, it still has practical limitations, as follows. (a) The process air may carry the corrosive desiccant droplets and damage the devices [6]. (b) Regeneration systems are often complex and large [7]. (c) Rotation of the desiccant wheels or the flow of liquid desiccants may cause noise and even lead to safety risks [8].

As a kind of humidity independent control methods, electrochemical dehumidification processes have drawn many attentions in these years. This kind of systems can drive the moisture transfer directly by an electric field, without the use of cooling water or desiccants. So the system can be simple and compact, requiring

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Nomenclature

A_{area}	Pem area [m^2]
a	water vapour activity [–]
c_p	specific heat [J/(kg K)]
D_v	water vapour diffusion coefficient [m^2/s]
D_w	water diffusion coefficient [m^2/s]
E_w	membrane equivalent weight [kg]
F	Faraday's constant [C/mol]
h	enthalpy [kJ/kg]
i	electric current density [A/m^2]
i^{ref}	electrode reference current density [A/m^2]
m	mass flow rate [kg/s]
$\dot{n}_v$	moisture molar reaction rate [mol/(s m^3)]
n_d	electro-osmotic drag coefficient [–]
q	heat [W]
u	velocity [m/s]
U	potential [V]
z	stoichiometric coefficient for transferred electrons [–]
α	charge transfer coefficient [–]
ρ	density [kg/m^3]
δ	thickness [m]
ζ	moisture mole concentration [mol/m^3]
λ	thermal conductivity coefficient [W/(m K)]
σ	electronic conductivity [S/m]
γ_0	specific reaction area [m^2/m$^{3]}$
χ	membrane water content [–]
η_{de}	dehumidification efficiency [kg/(s V m^2)]
η	over-potential [V]

Subscripts

a	air
p	process air
s	sweep air
A	anode side
C	cathode side
DL	diffusion layers
CL	catalyst layers
PEM	PEM membrane layer
in	inlet
out	outlet

only power supply instead of cooling and/or regeneration components. The researchers studied such methods as electro-osmotic [9,10], thermoelectric [11–13], electrodialysis [14,15] and electrolytic [16] variants. However, the thermoelectric dehumidification still has condensation problems, and the electro-osmotic and electrodialysis ones are not suitable for practical uses. Recently, the dehumidification with electrolytic materials is a creative and innovative technology. So, this study focused on the electrolytic air dehumidification system.

The electrolytic dehumidification with solid electrolytic materials was firstly proposed by Iwahara et al. in 2000 [17]. Then, Greenway et al. [18] and Sawada et al. [19] tested the water vapour removal possibility within electrolytic cells. However, the above studies were conducted at high temperatures (>600 °C). The possibility of electrolytic dehumidification at normal temperatures (20–40 °C) was experimentally validated by Sakuma et al. in 2009 [20]. In 2010, they also measured the effect of air temperature in an enclosed space, and built an empirical formula [21]. Then in 2011, Lewis et al. conducted an experiment [22], and developed an electrochemical model to simulate the water transfer [23]. In their study, only pure water vapour was used, rather than the actual airflow through the element. In 2017, Qi et al. validated the possibility of polymeric electrolyte membrane-based (PEM-based) electrolytic dehumidification with airflows [16]. The elements developed were compact, as small as 10^{-2}–10^{-3} m^3/kW. Additionally, the dehumidification performance was competitive to other electrochemical methods. A semi-empirical model was also developed for evaluating the performance. The comparison of different dehumidification methods was summarized in Table 1.

From the literature it could be found that the key advantage of the PEM-based dehumidification is its compact size and the ability in effective humidity control, which is suitable for industrial environments. However, most previous studies only focused on experiments. Until now, the system performance could only be predicted by empirical models. These models were seriously limited to the developers' experimental conditions, leading to discrepancies in different studies. Furthermore, different layers of the PEM-based element cannot be discerned in previous models, and the influence of airflows was not considered. So, the internal heat and mass transfer of the PEM-based dehumidification element was not yet clear. Without accurately predicting the effects of operating parameters on dehumidification performance, the system optimization became very difficult. Therefore, the development of a theoretical model for the electrolytic dehumidification element is of great significance to the practical applications of this novel system.

Table 1
Comparison of different dehumidification technology.

Dehumidification method	Working principle	Application in electronics and precision manufacturing
Cooling	Condensing water vapour with 7–12 °C cooling water	Insufficient humidity control, low system efficiency and condensation-induced water droplets [5]
Liquid desiccant	Dealing with water vapour with liquid desiccants	The process air may carry the corrosive desiccant droplets and damage the devices [6]
Membrane-based liquid desiccant	Absorbing vapour with liquid desiccants through high-selective membranes	Complex system. And regeneration systems are often large [7]
Desiccant wheel	Dealing with water vapour with solid desiccants	Rotation of the desiccant wheels may cause noise and even lead to safety risks [8]
Thermoelectric	Using Peltier effect to provide cool surfaces for dehumidifying	It still has the condensation problem like cooling dehumidification [11]
Electro-osmotic	Driving the vapour transfer with the electro-osmotic effect	Surrounding air should be over-saturated, making it not suitable for practical systems [9]
Electrolytic	Removing the extra vapour with electrolytic reactions and electro-osmotic effect	The system is compact and safe, which could control the air humidity accurate and effective [16]