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Capacitive deionization regeneration as a possible improvement of membrane regeneration method for absorption air-conditioning system

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HIGHLIGHTS

- The actual COP of the membrane regeneration system is 1–2.
- We propose the capacitive deionization regeneration method as an improvement.
- The CDI based system has higher performance, lower cost and better maintenance.
- The energy recovery strategy of the CDI based system can enhance the COP by 100%.

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ABSTRACT

Driven by renewable energy and being environment friendly, the absorption air-conditioning system is a good choice for green buildings. Concentrating the absorbent solution with electrodialysis method, the membrane regeneration absorption system has higher performance than the traditional absorption system. Its theoretical coefficient of performance can approach 6 under certain working conditions. However, the experimental data in this paper reveals the actual coefficient of performance of the membrane regeneration system is about 1–2, much lower than expected. It is caused by the energy loss in heating and electrochemical reactions. To improve, a capacitive deionization regeneration method is proposed: strong absorbent solution and pure water are acquired with the joint work of two units. Analysis has been made on the absorption air-conditioning system adopting this method. The mass and energy equations have been developed and some parameters have been investigated for performance optimization. Even with conservative prediction, the results show the capacitive deionization method has better performance than the membrane regeneration method. The coefficient of performance can be enhanced by 100% with the energy recovery strategy. Capacitive deionization method also has advantages on the cost and maintenance, which makes it a promising choice for the absorption air-conditioning system.

1. Introduction

A low carbon society calls for the reduction of energy from the combustion of fossil fuels. Today's buildings take up more than 40% of the total energy supply [1–3]. More than 30% of the energy supply to buildings is consumed by the air-conditioning systems. The widely used vapor compression system is not a green option, as it heavily depends on the electric power and the refrigerant causes some environmental problems. Absorption air-conditioning system could be a good alternative. It adopts environment friendly refrigerant (like water) and favours renewable energy (like solar energy) [4,5].

One bottleneck for the absorption system development is the lower performance compared with the vapor compression system. Many researches have been made to improve it. Multi-stage absorption and double effect absorption system bring in many advantages [6–8]. Combination system is also a good idea [9–12]. Gadhamshetty et al. have made progresses on a combination system consists of a desalination system and an absorption system [13]. Han, Jain, Seyfouri et al. concentrated on absorption–compression system [10,14,15]. Garousi Farshi et al. presented works on ejector–absorption combined system [9,16]. Gogoi designed a combined power/cooling cycle with higher performance [17]. Membrane regeneration is an emerging method

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Nomenclature

C	capacitance (F)
CDI	capacitive deionization
Con	mass concentration (%)
Con_{mol}	mole concentration (mol m^{-3})
COP	coefficient of performance (–)
ED	electrodialysis
F	Faraday constant (s A mol^{-1})
I	current intensity (A)
l_w	latent heat of water vaporization (kJ kg^{-1} K^{-1})
M_s	molecular weight of the solute in the absorbent solution (kg mol^{-1})
m	mass flow rate (kg s^{-1})
m_{mol}	mole transfer rate (mol s^{-1})
m_v	volume flow rate (m^3 s^{-1})
N	cell number (–)
N_{CDI}	number of electrode pairs (–)
P_{de}	energy consumption of deionization (kW)
P_{rec}	energy recovery of the regenerator (kW)
P_{CDI}	energy consumption of the CDI regeneration method (kW)
Q_0	cooling capacity (kW)
S	area (m^2)
T	time (s)
U	voltage (V)
V_t	charging time (s)
z	electrochemical valence (–)
Greek letters	
λ	charge efficiency (%)
μ	overall solute permeability coefficient (m s^{-1})
ρ	density (kg m^{-3})
ζ	current utilization efficiency (%)
η	energy recovery ratio (%)
Subscripts	
a	absorber
c	concentrated cell
i	in
o	out
r	regenerator
s	solute
w	water

for performance enhancement [18]. We have made research on a membrane regeneration absorption system driven by electric power [19,20]: A membrane regenerator replaces the generator and condenser of the traditional system. The regeneration is similar to an electrodialysis (ED) process [21–23]. Absorbent solution is concentrated in an electrical field with alternatively placed anion and cation exchange membranes. Small scale electric power supply (like solar photovoltaic or wind power) can meet its need. Through analysis, it found the COP of this system is higher than that of the traditional absorption system. The highest value could reach 6 under certain working conditions [19]. However, this conclusion lacks experimental support. This paper has presented the experiment work investigating the actual performance of the membrane regeneration system. The results expose the actual energy efficiency was 30–50% and the COP was only half of the theoretical value. The low efficiency is caused by energy loss in heating and electrochemical reactions, which partly attributes to the membrane resistance and high voltage (30–50 V). Expensive cost and fragility of the membrane are also disadvantages. These factors negatively influence the application of the membrane regeneration system. To improve, we propose a capacitive deionization (CDI) regeneration method. CDI is a technique that deionizes water by adsorbing the ions with charged electrodes. It stores energy in the form of a capacitor [24–29]. When the electrodes uncharged, ions are desorbed and enter into the solution, thus making the solution concentrated. According to the principle, two CDI units configure the regeneration part of the absorption air-conditioning system. They alternate their roles as the regenerator and deionizer, both the strong absorbent and pure water are acquired. Unlike ED, the CDI regeneration method uses electrode pairs instead of membranes and the applied voltage is below 1.23 V [29]. So it overcomes the negative effects from the membrane resistance and electrochemical reactions. Energy recovery is another advantage of the CDI regeneration method. By connecting the two units through an external circuit, the stored energy in the electrodes (capacitor) can be reused, which improves the efficiency. Analysis has been made on the CDI regeneration method. Compared with the membrane regeneration system, the CDI based system has a better performance.

2. Material and method

2.1. Experimental research of the membrane regeneration method

Fig. 1 presents the flow chart of the membrane regeneration air-conditioning system. The absorption and evaporation processes are same as that of the traditional system. A membrane regenerator replaces the generator and condenser. The regenerator is an ED stack. Ions concentrate in specified compartments by selectively passing through the cation exchange membrane (CM) or the anion exchange membrane (AM) [21–23]. In the regeneration process: cations are only allowed to pass through CM while anions are only allowed to pass through AM; solution is concentrated and diluted in alternating compartments under electrical field [21]. In this way, the weak solution from the absorber becomes strong in the concentrated cells and returns back to the absorber (Fig. 1). Solution from the diluted cells cycles through Solution Storage Tank 1 or 2 for repeated use and keeps the mass flow balance. A water storage pool is used to store pure water acquired in the regeneration process [19,20]. The solar PV part is a symbol of the energy supply. It can be replaced by other renewable energy sources (like wind power). It provides the flexibility and energy conservation potential of the system.

The coefficient of performance of the system is [19]:

$$COP = \frac{l_w(1 - Con_{oc})\zeta\ NM_s}{zFUCon_{oc}} \quad (1)$$

l_w is the latent heat of water vaporization. Con_{oc} is the solution mass concentration at the exit of the concentrated cells of the regenerator. ζ is the current utilization efficiency. N is the number of cell pairs. M_s is the molecular weight of the solute. z is the valence, and F is the Faraday constant. U is the applied voltage. Current utilization efficiency ζ is a measure of how effective ions are transported across the ion exchange membranes for a given applied current. It is defined as [21–23]:

$$\zeta = \frac{zFm_{cv}(Con_{ocmol} - Con_{icmol})}{NI} \quad (2)$$

m_{cv} is the volume flow rate of concentrated solution. Con_{icmol}, Con_{ocmol} are respectively the mole concentration at the entrance and exit of the concentrated cells. I is the current intensity.