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The potentials of capacitive deionization regeneration method for absorption air-conditioning system

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ABSTRACT

In favour of renewable energy and being environmental friendly, the absorption air-conditioning system is a good choice for developing low carbon society. However, the performance of the traditional absorption system is not quite good with big energy waste in the regeneration process. To improve, a capacitive deionization (CDI) regeneration method is proposed: in an electric field, strong absorbent solution and pure water are acquired with the joint work of two CDI units. Theoretical and experimental research are presented. Mass and energy models have been developed and some important parameters have been investigated. Primary tests have been conducted on the regeneration process. It shows the theoretical results agree well with the experimental results. The analysis exposes the influences of solution concentration, voltage and absorbent variety. The COP of the CDI based system approached 2 in the experiments, and it could be doubled with the unique energy recovery strategy. These indicate CDI a promising regeneration method for an absorption air-conditioning system with better performance.

1. Introduction

A low carbon society is a more energy efficient society. All systems should be more energy conservative to reduce the combustion of fossil fuels. This is especially true for today's buildings, which take up more than 40% of the total energy supply [1–3]. In buildings, more than 30% of the energy supply is consumed by the air-conditioning system. The widely used vapour compression system heavily depends on the electric power while the refrigerant brings environmental problems. As an alternative, absorption air-conditioning system could be a better choice, as it favours renewable energy and is more environment friendly [4,5].

One bottleneck for the absorption system development is the lower performance compared with the vapour compression system. Many researches have been made attempting to improve it. Multi-stage absorption and double effect absorption system are effective methods [6–8]. Combination system is also a good idea [9–12]. Gadhamshetty et al. made progresses on a combination system consists of a desalination system and an absorption system [13]. Zheng, Jain, Seyfouri et al. concentrated on absorption–compression system [14–16]. Garousi Farshi et al. presented works on ejector-absorption combined system [10,17]. Gogoi designed a combined power/cooling cycle with higher performance [18]. Membrane regeneration is an emerging method for performance enhancement [19]. We have made researches on a membrane regeneration absorption system driven by electric power [20–22]: A membrane regenerator replaces the generator and condenser of the traditional system. It is similar to an electrodialysis (ED) process [23–25]. 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. Avoiding the energy waste in heating mode, its theoretical COP is higher than that of the traditional absorption system and could reach 6 under certain working conditions [20]. However, the actual performance is only about 1.5 with the low actual energy efficiency, which was 30–50% in experiments, far below the assumed 90% [22]. It is caused by the energy loss in membrane resistance heating and electrochemical reactions under high voltages (30–50 V) [22]. Besides, the ion exchange membrane is expensive (700 dollars/m^2) and fragile. These make the membrane regeneration method less attractive. On the purpose of improvement, we propose a capacitive deionization (CDI) regeneration method in this paper. CDI is a rapidly emerging water treatment technique that promotes the adsorption of ions in the electrochemical double layer (EDL) of a charged electrode surface by applying an electric potential. In this way, it stores energy in the form of a capacitor and producing deionized water [26–31]. In

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Nomenclature

C	capacitance (F)
Con	mass concentration (%)
Con_{mol}	mole concentration (mol/m^3)
COP	coefficient of performance (dimensionless)
F	Faraday constant (s A/mol)
I	current intensity (A)
l_w	latent heat of water vaporization (kJ/(kg K))
M_s	molecular weight of the solute in the absorbent solution (kg/mol)
m	mass flow rate (kg/s)
m_{mol}	mole transfer rate (mol/s)
m_v	volume flow rate (m^3/s)
N	cell number (dimensionless)
N_{CDI}	number of electrode pairs (dimensionless)
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 (dimensionless)

Greek letters

λ	charge efficiency (%)
η	energy recovery ratio (%)

Subscripts

a	absorber
i	in
o	out
r	regenerator
s	solute
w	water

the new system, 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 [31]. So it could overcome the negative effects of the membrane resistance heating and avoid the electrochemical reactions. The cost is also much cheaper. Another exceptional advantage is the energy recovery ability by connecting the two units through an external circuit. The stored energy in electrode (capacitor) can be reused, which greatly improves the efficiency [26,31]. Theoretical analysis and primary experimental research have been made on the CDI regeneration method. The results show it has potential to make absorption system more competitive.

2. Material and method

2.1. Principle of the capacitive deionization process

Fig. 1 is the schematic of the electro-sorption/desorption process of a CDI unit [32]. When the electrodes are charged by applying a potential to the solution, the ions are adsorbed on the electrodes, thereby producing deionized water at the outlet (Fig. 1 (left)). The potential difference would not exceed the Nernst voltage or the standard electrode potential of water. It is below 1.23 V across the electric double layer, hence no hydrolysis will happen. In the regeneration step, Fig. 1 (right), a wash solution is circulated while the electrodes are depolarized. Ions are desorbed from the electrodes and pass into the bulk of the solution, resulting in a stream of higher concentration. These two stages are essentially the same as charging and discharging an electrochemical double layer capacitor.

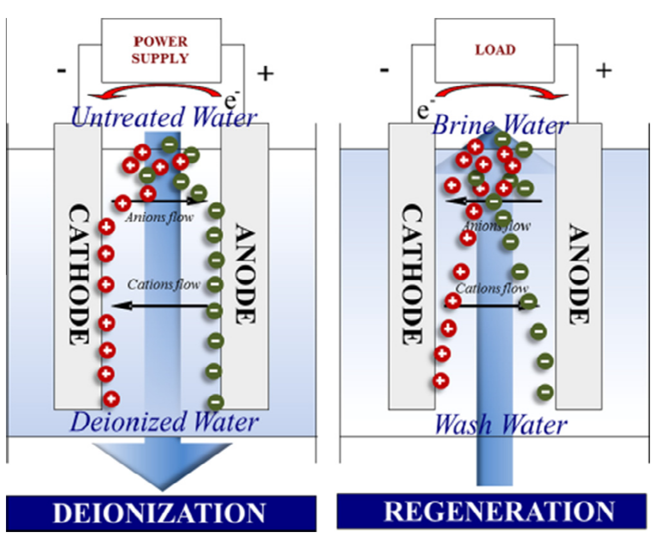

Fig. 1. Principle of the capacitive deionization process [30].

Deionization (charging) and regeneration (discharging) involves reversible electro-adsorption with electrochemical response behaving in a purely capacitive fashion without any Faradaic (redox reactions) contribution. This allows one to recover a portion of the energy during regeneration, much as in a double-layer capacitor during discharge. Compared with ED method, CDI method avoids the energy loss with the membranes and electrochemical reactions. Plus the energy storage ability, it could be more energy efficient.

2.2. Capacitive deionization regeneration method for the absorption air-conditioning system

Based on the principle of CDI, a new regeneration method is proposed for the absorption air-conditioning system. Fig. 2 shows the flow chart: the absorption and evaporation processes are same as the traditional system. The regeneration is completed with the joint work of two CDI units. The two units alternate their roles as the regenerator and deionizer to produce both the strong absorbent solution and pure water. Meanwhile, the units are connected with a DC/DC converter. It will transform the variable *V–I* curve into a constant current or constant voltage supply [33]. Through the connection, the regenerator also works as a discharging capacitor and applies the stored energy to deionize the solution passing through the deionizer. Figs. 3 and 4 present the processes in detail.

In Fig. 3, CDI Unit 1 gets the electrodes saturated with ions and works as the regenerator. The pink and red lines depict the regeneration cycle. Valves 1, 2 and 5 are open, Valve 3, 4 are closed. The weak solution from the absorber is sent to CDI Unit 1, where the adsorbed ions release from the electrodes and enter the solution.