Investigation of heat and mass transfer characteristics during energy discharge in an energy storage unit using hollow fiber membranes

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ABSTRACT

A novel concentration difference energy accumulator was evaluated. This accumulator was framed by hollow fiber membranes as the water vapor transfer channels. This was the membrane energy accumulator (MEA). A mathematical model was created to simulate the heat and mass transfer in the crystal dissolving process of the energy discharging stage. In addition, the model was experimentally validated. Based on the simulation results, the heat and mass transfer characteristics of the MEA in the crystal dissolving process were analyzed. The results of the simulation and experiments proved the feasibility of the MEA. The energy storage capacity of the MEA was a minimum of 25% greater than that of a traditional concentration difference energy accumulator. The effectiveness of the MEA was confirmed.

1. Introduction

For a solution concentration difference storage (SCDES) system, the thermal energy is stored as the chemical potential of the solution by increasing the difference in the solution concentration. In the energy storage stage, the heat loss of the energy accumulator does not reduce the chemical potential of the solution. Conversely, the heat loss will decrease the solution temperature and then increase the chemical potential (cooling capacity) of the solution. Moreover, the chemical potential of the solution will transform into thermal and cooling energies by simple technical methods [1].

An SCDES system could improve the application feasibility of solar powered lithium bromide (LiBr) cooling technology. Solar energy utilization would be improved. However, a traditional SCDES system has two issues when it is used in a solar powered LiBr cooling system (SPLBCS). The LiBr solution is expensive, and the concentrated solution crystallizes. In a long-term thermal storage system, crystallization of the lithium bromide/water solution has little impact on the performance of the system because of the slow discharging process [2,3]. However, in a transient SPLBCS, the crystal will retain the concentrated solution in the accumulator flowing into the absorber. Therefore, the discharge process is difficult. Meanwhile, the crystal existing in a traditional accumulator

will not easily dissolve because of inadequate heat and mass transfer. Therefore, crystallization is not acceptable in a traditional SCDES. The mass fraction of the stored solution is low. Therefore, the energy storage capacity will be not meet the application requirement of a low investment in a SPLBCS.

To overcome this drawback, we proposed a novel membrane energy accumulator (MEA). In the MEA, the mass transfer channels between the vapor and solution were framed by the semi-permeable membranes. The membranes increased the contact interface area between the water vapor and solution. When the concentrated solution stored in the MEA was crystallized, the water vapor molecules from the evaporator diffused into the solution through the semi-permeable membranes in the energy discharging process. The absorption heat was released, and the temperature of the solution increased. Therefore, the crystal dissolved. Crystallization would not be an obstacle in the energy accumulator. Conversely, crystallization could improve the energy storage capacity because a stronger solution could be stored in the MEA.

The membranes used in the MEA have similar characteristics to those used in membrane distillation for water desalination and purification applications as well as air dehumidification and heat recovery in heating, ventilation and air-conditioning (HVAC) systems. Using this membrane, a tiny pressure difference created mass transfer through the membrane; therefore, low energy was required, and the solar energy or waste heat was used as the heat source [4,5]. A membrane separation technique has been success-

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Nomenclature

A, k	coefficient
c	specific heat, J/(K·kg)
D_{ab}	molecular diffusion coefficient of the LiBr solution, m²/s
K_m	permeation flux
M	molecular weight of the water vapor, kg/mol
N	trans-membrane flux, kg/(m²·s)
h_f	heat convection coefficient
H_v	dissolution heat, J/kg
P	pressure, Pa
r_0	radius of the micropore, m
R	gas constant, J/(mol·K)
T	temperature, K
TD	dew point temperature of the water vapor
v_z	velocity of the water vapor in the z-direction, m/s
w	mass fraction of the solution

ΔP	pressure difference, Pa
ε	porosity of the membrane
ρ	density, kg/m³
λ	heat conductivity coefficient, W/(K·m)
τ	time, s
τ_m	tortuosity factor of the micropore
τ_w	friction between the water vapor and internal membrane wall, N/m²

Subscripts

e	effective
f	water vapor
g	water vapor
l	LiBr solution
m	membrane

Greek letters

δ_m	thickness of the membrane wall, m

fully used in HVAC systems for heat recovery and desiccant dehumidification because the temperature is not required to be below the air dew point temperature to condense the excess moisture. A liquid air membrane energy exchanger (LAMEE) is a membrane application example in HVAC systems. Zhang [6] showed that 70–80% of the energy for conditioning fresh air could be saved for the dehumidification application of the membrane. For a compression heat pump driving air dehumidification system with hollow fiber membrane-based two-stage liquid desiccant, the coefficient of performance (COP) could be increased by approximately 20%under the hot and humid conditions of southern China [7]. Namvar et al. [8] experimentally investigated the influence of the number of heat transfer units and the ratio between the heat capacities of a desiccant solution and the air ratio of the heat capacity rate values on the transient and steady-state performance of an LAMEE. In the LAMEEs, the air and solution channels were separated by flat membranes [9]. The solution and air flows contained a counterflow arrangement. Water vapor molecules in the air permeated into the saline solution through the flat membrane under the water vapor partial pressure difference. Vali et al. [10] studied the fluid flow coupled with the heat and mass transfer of a counter-crossflow LAMEE. Das and Jain [11] studied various flat plate membrane contactors for membrane-based indirect contact liquid desiccant dehumidification applications. The performance of the contactors was dependent on the membrane characteristics, porosity, pore size, and thickness. Min and Su [12] studied the membrane parameters, including the moisture diffusivity, thermal conductivity, moisture sorption constant, and maximum moisture uptake for an air-to-air crossflow membrane energy exchanger (MEE). The thermal conductivity of the membrane had minimal influence on the sensible, latent, and enthalpy effectiveness. The hollow fiber MEE had a similar structure to a tube-shell heat exchanger. Zhang et al. [13] numerically and experimentally studied the hollow fiber membrane module used for liquid desiccant air dehumidification. The impinging angles had an impact on the flow and heat and mass transport in the bundle. However, the pressure drop in the solution was not investigated. To improve the steady-state performance of the LAMEE, Adbel-Salam et al. [14,15] placed cooling water tubes into the solution of the LAMEE as a heat sink and designed a 3-fluid LAMEE.

Though no research regarding the MEA has been reported, the research on the MEE contained valuable references for the MEA. Based on the MEE used in an HVAC system, we proposed using the MEA as a solution concentration difference accumulator used in an SPLBCS. The MEA was not impacted by air particulate, and the membrane in the MEA had a longer operation time than that in the MEE. In this study, a hollow fibrous MEA was designed, and its heat and mass transfer characteristics were numerically investigated. The numerical simulation was cost effective, required minimal time, was simple to convert to the working condition, etc. In addition, the numerical simulation results clearly showed the heat and mass transfer process in the MEA. In the experiments, the temperature and mass fraction fields of the solution in the MEA were difficult to test because of the thin solution layers. Therefore, the average temperature and mass fraction of the solution in the MEA were tested to validate the mathematical model created in this study and to verify the feasibility of the MEA. Through the analyses of the heat and mass transfer characteristics in the MEA, the methods to improve the heat and mass transfer performance and increase the energy storage capacity were determined.

2. Membrane energy accumulator

In the SPLBCS, the MEA was placed in the system, as shown in Fig. 1(a). When the heat from the solar thermal collectors was more than that consumed by the cooling system, switching valve V1 opened. Valves V2 and V3 remained closed. The concentrated solution flowed into and was stored in the MEA. When the heat from the solar thermal collectors was insufficient, the switching valve V2 opened and the concentrated solution stored in the MEA flowed into the absorber. The cooling discharge began in the absorber. However, valve V3 opened when the solution stored in the MEA crystallized owing to the higher mass fraction. The solution in the MEA absorbed the water vapor from the evaporator. The cooling discharge began in the MEA. When the crystal in the MEA melted, the concentrated solution in the MEA flowed into the absorber, as in a traditional solution accumulator.

Fig. 1(b) shows the schematic diagram of the hollow fiber MEA module, which could be housed by a shell, as in the MEA (Fig. 1(a)). In the MEA module, the water vapor channels were framed by micro-porous membranes, as shown in Fig. 1(b). The water molecules permeated into the solution through the membrane; however, the LiBr ions were prevented from permeating into the water vapor channels. In the hollow MEA module, the solution