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Numerical investigation of the thermal performance of compressor-assisted double-effect absorption refrigeration using [mmim]DMP/CH_3OH as working fluid

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ABSTRACT

The thermal performance of compressor-assisted double-effect absorption refrigeration (CDAR) was numerically investigated and comprehensively analyzed with 1, 3-dimethylimidazolylium dimethylphosphate/methanol ([mmim]DMP/CH_3OH) as working fluid. The CDAR system was modeled and simulated based on the proposed mathematical model of the compression process by considering the mass and energy conservation of each component. The effects of compression ratio and heat source temperature on the system's operating state, including solution temperature, refrigeration concentration, mass flow, and heat load of each component, were calculated and discussed. Variations in the coefficient of performance and exergy efficiency in four cases were simulated and compared. Results suggested that placing the assisting compressor between the evaporator and absorber was a good option, and placing the assisting compressor between two generators was also acceptable. The exergy losses of each component were calculated and compared. The largest exergy loss occurred in the low-temperature generator and accounted for approximately one-third of the total exergy input. The main reason for the exergy loss in the diffusion absorption refrigeration system was heat transfer with a temperature difference.

1. Introduction

Absorption refrigeration has been widely applied in low-grade heat sources [1], such as solar energy [2], geothermal energy [3], biomass energy [4], and industrial waste heat [5]. The working fluid of absorption refrigeration is composed of an absorbent and a refrigerant [6]. The main role of the absorbent is to reduce the saturated vapor pressure of the working fluid solution [7] to ensure absorption in the absorber of absorption refrigeration. Therefore, the absorbent is the key component of the working fluid.

Ionic liquids (ILs) are organic ionic compounds with melting points lower than room temperature [8]. ILs are miscible with most refrigerants, such as Freon, alkane, and alcohol [9]. The vapor pressure of a solution containing an IL and a refrigerant is largely reduced because the vapor pressure of ILs is negligible. Additionally, ILs possess excellent properties of high thermal stability, low combustibility, and non-corrosiveness [10]. Therefore, ILs are potential absorbents in absorption refrigeration.

The concept of using ILs as absorbents in absorption refrigeration was proposed by Yokozeki in 2006 [11]. Research on IL absorption refrigeration has become popular in recent decades. Shiflett et al. [12] investigated the thermal performance of absorption refrigeration using IL/Freon as working fluid. An optimal coefficient of performance (COP) of 0.539 for the DMF/R22 system was reported. Liang et al. [13] numerically investigated the cycle characteristic of IL absorption refrigeration using alcohols as a refrigerant. Su et al. [14] simulated the theoretical cycle of absorption refrigeration by adopting [hmim]Cl/H_2O and [Emim]AC/H_2O as working fluids. They found that the thermal performance of the [Emim]AC/H_2O system is better than that of [hmim]Cl/H_2O. Ángel et al. [15] investigated the possibility and potential of absorption refrigeration with IL/CO_2 as working fluid and indicated that the best absorbent for supercritical CO_2 is [bmpyrr][Tf_2N]. Shiflett et al. [16] investigated the thermal performance of the IL/NH_3 absorption system and discovered that absorption refrigeration using [DMEA][AC]/CO_2 achieves an optimal COP. They also confirmed that IL absorption refrigeration possesses an excellent industrial application potential.

The COP and generation temperature of multi-effect absorption refrigeration are significantly higher than those of a single-effect system. The most widely used working fluid in multi-effect absorption refrigeration is LiBr/H_2O [17]. The LiBr concentration in the solution from the generator increases with the generation temperature, and this

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Nomenclature

A, B, b	parameters for EOS of CH_3OH
AU	total heat conductance (kJ/K)
c_p	specific heat capacity (kJ/(kg·K))
COP	coefficient of performance
f	function
h	Specific enthalpy (kJ/kg)
L_b	latent heat (kJ/kg)
p	pressure (kPa)
q_m	mass flow (kg/s)
Q	heat flow (kW)
p	pressure (kPa)
s	specific entropy (kJ/(kg·K))
S_g	entropy production (kJ/K)
v	specific volume (m^3/kg)
w	specific power (kW/kg)
W	power (kW)

Greek symbols

γ	compression ratio
η	efficiency
φ	activity coefficient
ω	mass fraction

Subscript

1,2…16	status point
0	environmental
AB, A	absorber
act	actual process
C	critical parameter
CD	condenser
CM	compressor
EV	evaporator
ex	exergy
HG	high temperature generator
HX	high temperature exchanger
in, out	parameter of inlet and outlet
IL	ionic liquid
LG	low temperature generator
LX	low temperature exchanger
v	vapor

Superscript

0	reference point
E	excessive parameter
is	isentropic process
S	saturation

increment significantly increases the risk of crystallization in the solution heat exchanger [18]. In addition, the corrosion of LiBr/H_2O solution is extremely strong at high temperatures [19]. The application of multi-effect LiBr/H_2O absorption refrigeration is thus largely restricted. Multi-effect absorption refrigeration using IL as working fluid can completely prevent the problems of corrosion and crystallization in the LiBr/H_2O system because of the low melting temperature and non-corrosiveness of ILs. ILs as working fluid are more suitable for multi-effect absorption refrigeration than LiBr/H_2O.

However, the deflation range of IL absorption systems is smaller than that of LiBr/H_2O systems [13,14]. A small deflation range results in a high circulation ratio and causes COP deterioration [12,15]. The most reasonable approach to improve the deflation range is introducing an assisting compressor into the absorption cycle [20]. Boer et al. [21] numerically studied double-effect absorption refrigeration with a compressor placed between the evaporator and absorber and with TEGDME/CH_3OH and TEGDME/TFE as working fluids. Kim et al. [22] conducted simulations for a basic triple-effect cycle and four proposed compressor-assisted cycles with LiBr/H_2O as working fluid. Dereje et al. [23] investigated the thermal performance of a combined absorption power and refrigeration cycle with an integrated compressor. Wang et al. [24] numerically investigated the thermal performances of the absorption compression hybrid refrigeration system recovering condensation heat for generation. Shu et al. [25] simulated the thermal performance of a proposed compressor-assisted triple-effect LiBr/H_2O absorption cooling cycle coupled with a Rankine cycle driven by high-temperature waste heat. They reported that the integrated compressor improves the thermal performance of multi-effect absorption refrigeration.

In this study, a mathematical model of the compression process was established based on the equation of state (EOS), the enthalpy equation, and the entropy equation of superheated methanol vapor. Steady modeling and simulation of compressor-assisted double-effect absorption refrigeration (CDAR) system with [mmim]DMP/CH_3OH as working fluid were conducted in consideration of the mass and energy conservation of each component of the proposed system. The influences of compression ratio and heat source temperature on the operating states and thermal performance of the CDAR system were simulated and analyzed, and the exergy losses of each component were calculated and discussed.

2. Thermodynamic properties of working fluid

The vapor liquid equilibrium (VLE) of the [mmim]DMP/CH_3OH solution is crucial for the simulation of the thermal performance of the CDAR system. The vapor phase of [mmim]DMP/CH_3OH is pure CH_3OH vapor because the vapor pressure of [mmim]DMP is negligible. The vapor pressure of the [mmim]DMP/CH_3OH solution can be calculated as follows:

$$p = x_2\varphi_2 p_2^S \tag{1}$$

where x_2 is the mole fraction of CH_3OH in the solution, φ_2 is the activity coefficient of CH_3OH, and p_2^S is the saturation pressure of pure CH_3OH. φ_2 can be calculated using the universal quasichemical functional group activity coefficient (UNIFAC) model [26]. p_2^S can be calculated using the Antoine equation [27].

The specific enthalpy and entropy of the [mmim]DMP/CH_3OH solution are the most essential properties to the simulation of the thermal performance of the CDAR system. The specific enthalpy of the binary solution can be calculated as

$$h = \omega_1\int_{T^0}^{T} c_{p,\mathrm{IL}}\,dT + \omega_2\int_{T^0}^{T} c_{p,\mathrm{R}}\,dT + h_0^{\mathrm{E}} + \int_{T_0}^{T} c_p\,dT \tag{2}$$

The specific entropy of the binary solution can be calculated as [26]

$$s = \omega_1\int_{T^0}^{T} (c_{p,1}/T)dT + \omega_2\int_{T^0}^{T} (c_{p,2}/T)dT + h_0^{\mathrm{E}}/T_0 + \int_{T_0}^{T} (c_p/T)dT \tag{3}$$

where T_0 is ambient temperature, which is 298.15 K, and T^0 is the reference temperature for the calculation of specific enthalpy and entropy. The value of T^0 is 273.15 K. h_0^{E} is the excess enthalpy of the solution at T_0. ω_1 and ω_2 are the mass fractions of [mmim]DMP and CH_3OH in the binary solution, respectively. $c_{p,1}$ and $c_{p,2}$ are the specific heat capacities of [mmim]DMP and CH_3OH, respectively. c_p stands for the specific capacity of the [mmim]DMP/CH_3OH solution. The expression of h_0^{E} and the specific capacities can be found in our previous work [28].