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Novel ionic-liquid-based low-GWP working fluids used for hybrid low-temperature absorption cooling

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Abstract

Absorption cooling cycles are promising renewable/waste energy technologies for building energy efficiency. To overcome the two major shortcomings (working fluid and driving temperature) of conventional absorption cooling technologies, various ionic-liquid-based low-global-warming-potential working fluids were investigated for different hybrid low-temperature absorption cooling cycles. Results showed that the hybrid cycle not only greatly enhanced the coefficient of performance (COP) but also lowered the driving temperature from 60~70 ºC to below 45 ºC. R32 performed the best, with a maximum COP of 0.670, while R1234yf performed the worst, with a maximum COP of 0.430. The optimal compression ratio of the hybrid cycle is 1.9~3.4 for maximum COP and 1.3~2.2 for maximum exergy COP. The low-side hybrid absorption cycle is a better choice in terms of high cycle efficiency and low discharge temperature. This work can facilitate better utilization of lower-temperature renewable/waste energy.

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Keywords: Hybrid absorption cooling; Renewable and waste energy; Ionic liquid; Low GWP

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1. Introduction

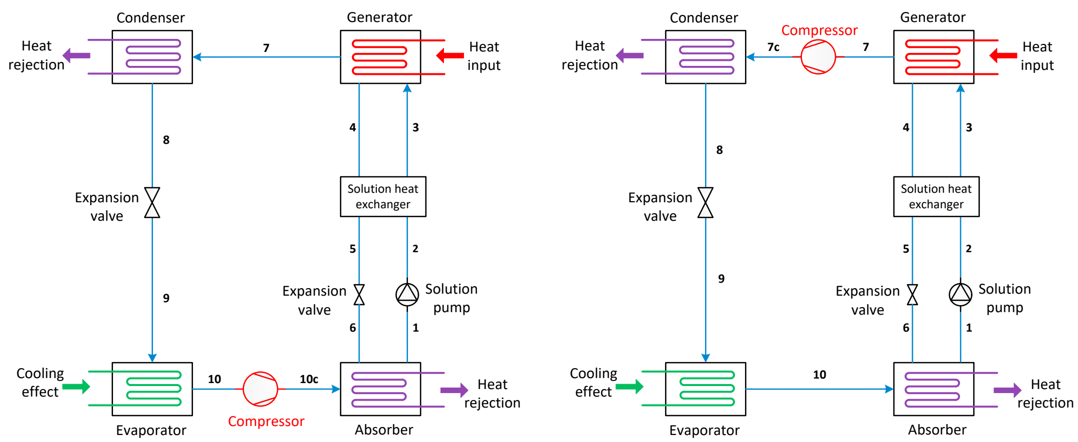
Global energy and environmental issues attract increasing interests in renewable and waste energy utilization. Absorption cooling cycles driven by renewable/waste energy are promising for building energy efficiency. However, the conventional absorption technologies have two major shortcomings in terms of working fluid and heat source temperature. First, the widely used H_2O/LiBr is impossible for sub-zero operations and suffers from crystallization, corrosion and negative pressure. NH_3/H_2O has concerns of toxicity and corrosion, while requiring the complex rectification [1]. Second, the conventional absorption cycle requires the driving temperature to be high enough, losing the capability to utilize renewable/waste energy with relatively lower temperatures. It is significant to explore alternative absorption cycles using novel working fluids to overcome these shortcomings. There are increasing studies on working fluids, among which the ionic liquids (ILs) are promising candidates due to their negligible vapor pressure, good stability, and sound solubility with many refrigerants [2]. The IL-based mixtures include H_2O/IL, NH_3/IL, hydrofluorocarbon (HFC)/IL, hydrofluoroolefin (HFC)/IL, alcohol/IL and CO_2/IL [3-5]. The low global-warming-potential (GWP) HFCs and HFOs feature good safety, reliability and environmental-friendliness. They have been rarely investigated for absorption cooling cycles, especially driven by lower heat source temperatures.

In this study, various novel low-GWP HFCs and HFOs paired with [hmim][Tf_2N] are considered for hybrid low-temperature absorption cooling. The energy and exergy performance are compared among different mixtures. The improvement of cooling performance and operation range contributed by the hybrid cycles are evaluated under different conditions. In addition, different hybrid cycles are compared for all the working fluids. The objective is to facilitate better utilization of renewable/waste energy through novel working fluids in advanced absorption cycles.

2. Principle of hybrid low-temperature absorption cooling

The compression-assisted absorption cycle is used for low-temperature driving. Depending on the compressor configuration, it can be low-side compression (Fig. 1(a)) and high-side compression (Fig. 1(b)). A lower generation temperature causes a smaller concentration difference, resulting in worse performance or disability to operate. It is essential to increase concentration differences, by auxiliary compression, under much lower generation temperatures.

The fundamental principles of basic absorption cycles can be found in [1, 2], and only the benefits contributed by compression are depicted here due to length limit. For the low-side compression hybrid cycle, the compressor can boost the absorption pressure from p_e (10) to p_a (10c). In this manner, the absorption process is strengthened, and the weak solution is much weaker after absorption, contributing to increased concentration difference. For the high-side compression hybrid cycle, the compressor can maintain the required condensation pressure p_c while reduce the generation pressure from p_c (7c) to p_g (7). In this manner, the generation process is strengthened, and the strong solution is much stronger after generation, also contributing to increased concentration difference.



(a) Low-side compression (b) High-side compression

Fig. 1. Schematics of hybrid absorption cooling cycles

3. Property and modeling methods

3.1. Property method of various refrigerant/IL pairs

The properties of the HFC/IL and HFO/IL mixtures (Table 1) are derived from the experimental vapor-liquid equilibrium (VLE) data, using the non-random two liquid (NRTL) activity coefficient property method [2]:

$$\exp\left[\frac{(B_i - V_i^L)(p - p_i^S)}{RT}\right] Y_i p = X_i \gamma_i p_i^S (i = 1, \dots, N) \quad (1)$$

where X_i and Y_i are liquid and vapor mole fractions of the i[th] species; p and p_i^S are system and saturated pressure, kPa; B_i is the second virial coefficient, cm^3/mol; V_i^L is saturated molar liquid volume, cm^3/mol; γ_i is activity coefficient [2]:

$$ln\gamma_1 = X_2^2\left[\frac{\tau_{21}G_{21}^2}{(X_1 + X_2G_{21})^2} + \frac{\tau_{12}G_{12}}{(X_2 + X_1G_{12})^2}\right] \quad ln\gamma_2 = X_1^2\left[\frac{\tau_{12}G_{12}^2}{(X_2 + X_1G_{12})^2} + \frac{\tau_{21}G_{21}}{(X_1 + X_2G_{21})^2}\right] \quad (2)$$

$$G_{12} = \exp(-\alpha\tau_{12}),\ \ G_{21} = \exp(-\alpha\tau_{21}) \qquad \tau_{12} = \tau_{12}^0 + \frac{\tau_{12}^1}{T},\ \ \tau_{21} = \tau_{21}^0 + \frac{\tau_{21}^1}{T} \quad (3)$$

where $\alpha, \tau_{12}^0, \tau_{12}^1, \tau_{21}^0, \tau_{21}^1$ are adjustable parameters, which represent binary interactions between component 1 (refrigerant) and component 2 (IL) and are regressed from experimental data [4, 5]. Table 1 lists the adjustable parameters of 6 mixtures, with the average absolute deviation (AAD) indicating the accuracy of the property model.

Table 1. Adjustable parameters of the NRTL model for HFC/IL and HFO/IL working pairs

Working pair	α	τ_{12}^0	τ_{12}^1	τ_{21}^0	τ_{21}^1	AAD (%)
R134a/[hmim][Tf$_2$N]	0.6481	-11.84	5069	-4.572	1428	5.5
R32/[hmim][Tf$_2$N]	0.8752	0.8717	-136.1	-0.2574	-151.4	1.8
R152a/[hmim][Tf$_2$N]	2.266	-0.2019	-25.23	-0.6005	414.9	0.7
R161/[hmim][Tf$_2$N]	0.2456	-0.9312	-239.7	0.7522	587.9	2.9
R1234yf/[hmim][Tf$_2$N]	0.2096	20.17	-1923	36.49	-1654	0.7
R1234ze(E)/[hmim][Tf$_2$N]	-12.83	0.3359	-76.07	0.2888	80.25	1.2

The enthalpy of binary mixtures can be calculated by [2]:

$$H = X_1H_1 + X_2\left(\int_{T_0}^{T} C_{p,IL}dT + H_0\right) + H^E \qquad H^E = -RT^2\left[X_1\left(\frac{\partial ln\gamma_1}{\partial T}\right)_{p,x} + X_2\left(\frac{\partial ln\gamma_2}{\partial T}\right)_{p,x}\right] \quad (4)$$

where H_1, H_0 and H^E are liquid refrigerant enthalpy, reference enthalpy and mixture excess enthalpy, J/mol; T_0 is reference temperature (273.15 K); $C_{p,IL}$ is the IL heat capacity, J/(mol·K); R is the universal gas constant, J/mol·K.

3.2. Model establishment and verification

Assuming that the system is in steady state; the refrigerants leaving the evaporator and condenser are both saturated; the solutions at the generator and absorber outlets are in phase equilibrium; the pressure and heat losses are ignored; the throttling process is isenthalpic. The solution heat exchanger effectiveness is 0.8, and the compressor isentropic efficiency is 0.7. The models are established based on the mass and energy balances:

$$\sum m_{out} = \sum m_{in} \qquad \sum m_{out}x_{out} = \sum m_{in}x_{in} \qquad W + Q + \sum m_{in}h_{in} = \sum m_{out}h_{out} \quad (5)$$

where m, h and x are mass flow (kg/s), specific enthalpy (kJ/kg) and mass concentration; W and Q are power and heat duty, kW. The coefficient of performance (COP) and exergy COP are respectively defined as:

$$COP = \frac{Q_e}{\left(Q_g + \frac{W_c}{\eta_e}\right)} \qquad ECOP = \frac{Q_e\left|1 - \frac{T_0}{T_e}\right|}{Q_g\left(1 - \frac{T_0}{T_g}\right) + W_c} \quad (6)$$

where η_e is electricity generation efficiency (0.38 [6]); T_0 is reference temperature for exergy calculation (298.15 K).

To verify the model, the calculations are compared with the existing studies. Fig. 2 presents the comparison for a single-effect cycle using H_2O/[dmim][DMP] under condensation, absorption and evaporation temperatures of 40 °C, 30 °C and 10 °C [2]. Good agreements are reached between the model and the reference, in terms of cooling COP, operation range and performance trend. Though with a different fluid, Fig. 2 verifies the cycle model while Table 1 proves the accuracy of the property model. Thus, the established models are suitable for the following analysis.

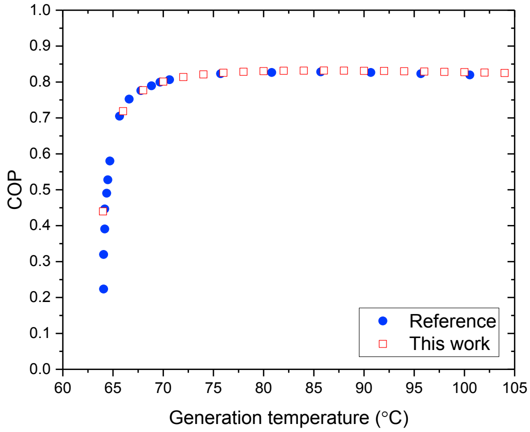
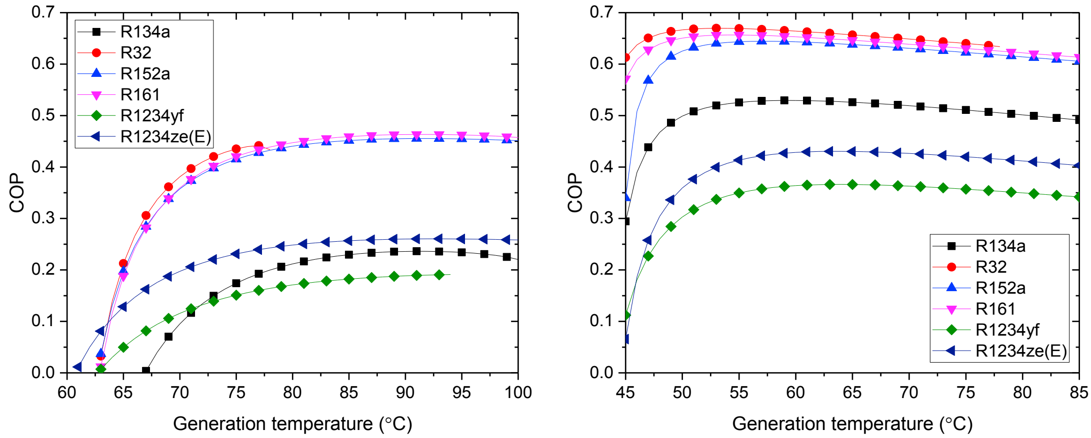


Fig. 2 Model verification of the single-effect absorption cycle using H_2O/[dmim][DMP]

4. Results and discussions

4.1. *Comparison of energy efficiency*

Fig. 3 shows the COP comparison between basic and hybrid (low-side compression, compression ratio CR=1.5) absorption cooling cycles using different IL-based working pairs. For both cycles, R32 yields the highest COP, followed by R161 and R152a with slightly lower COPs. R1234yf performs the worst in most conditions; R134a performs worse than R1234ze(E) with the basic cycle but outperforms R1234ze(E) with the hybrid cycle. The hybrid cycle not only greatly enhance the COP but also effectively lower the generation temperature. The maximum COP is improved from 0.442, 0.463, 0.455, 0.236, 0.260 and 0.191 to 0.670, 0.657, 0.644, 0.529, 0.430 and 0.366 for R32, R161, R152a, R134a, R1234ze(E) and R1234yf, respectively. In addition, the minimum generation temperature is lowered from 60~70 ºC to below 45 ºC.

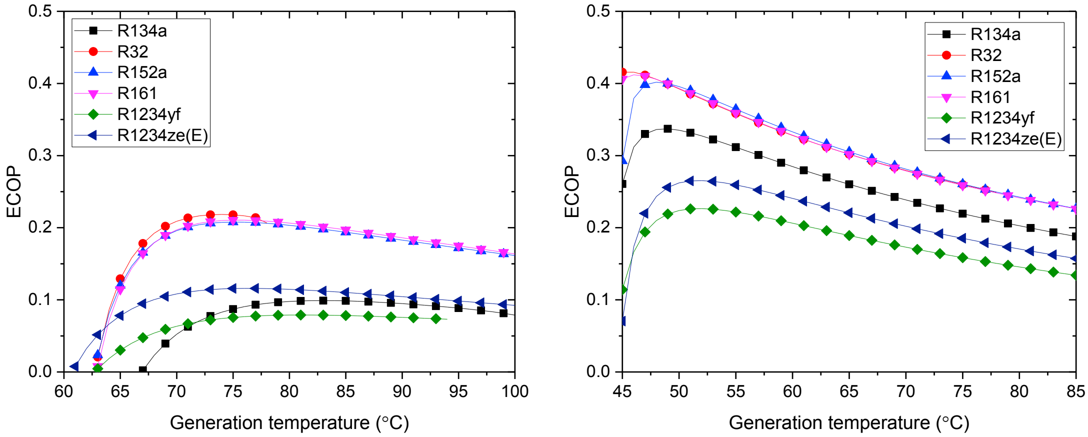


(a) basic cycle (b) hybrid cycle

Fig. 3. COP comparison between basic and hybrid absorption cooling cycles (T_a=T_c=30 ºC, T_e=5 ºC, CR=1.5)

4.2. *Comparison of exergy efficiency*

Fig. 4 shows the ECOP comparison between basic and hybrid (low-side compression) absorption cooling cycles. The ECOP follows similar behaviors of COP among the various working pairs. With the hybrid absorption cooling cycle, the maximum ECOP is improved from 0.218, 0.211, 0.208, 0.099, 0.116, and 0.079 to 0.416, 0.412, 0.402, 0.337, 0.265 and 0.226 for R32, R161, R152a, R134a, R1234ze(E) and R1234yf, respectively.

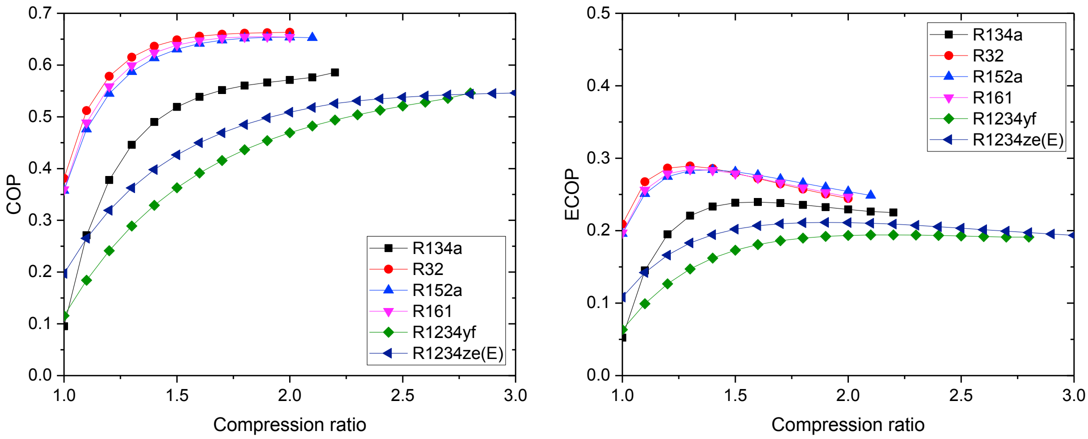


（a） basic cycle (b) hybrid cycle

Fig. 4. ECOP comparison between basic and hybrid absorption cooling cycles (T_a=T_c=30 ℃, T_e=5 ℃, CR=1.5).

4.3. Optimization of compression ratio

Fig. 5 shows the COP and ECOP of the hybrid (low-side compression) cycle under various compression ratios. As the compression ratio increases, both COP and ECOP increase fast first and increase slowly or even decrease later. Because a higher compression ratio contributes to better absorption or generation process but leads to higher compressor electricity consumption, which is of higher energy grade. The compression ratio could not be too high, constrained by the solubility. There is an optimal CR at which the COP or ECOP peaks. The optimal CR to achieve maximum COP is 2.0, 1.9, 2.0, 2.2, 3.4 and 2.8 for R32, R161, R152a, R134a, R1234ze(E) and R1234yf, respectively. The optimal CR to achieve maximum ECOP is respectively 1.3, 1.3, 1.4, 1.6, 1.9 and 2.2.

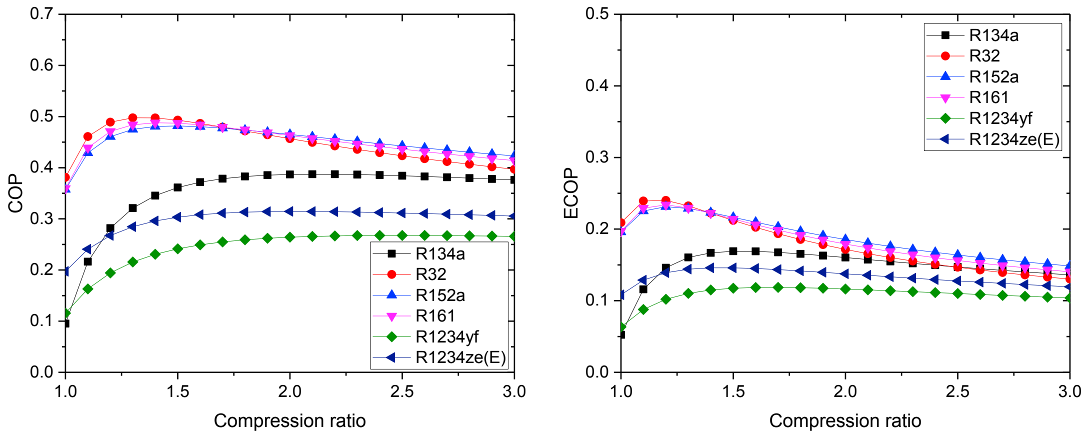


（a） COP (b) ECOP

Fig. 5. Effect of compression ratio on COP and ECOP of the hybrid absorption cooling cycle (T_a=T_c=30 ℃, T_e=5 ℃, T_g=70 ℃)

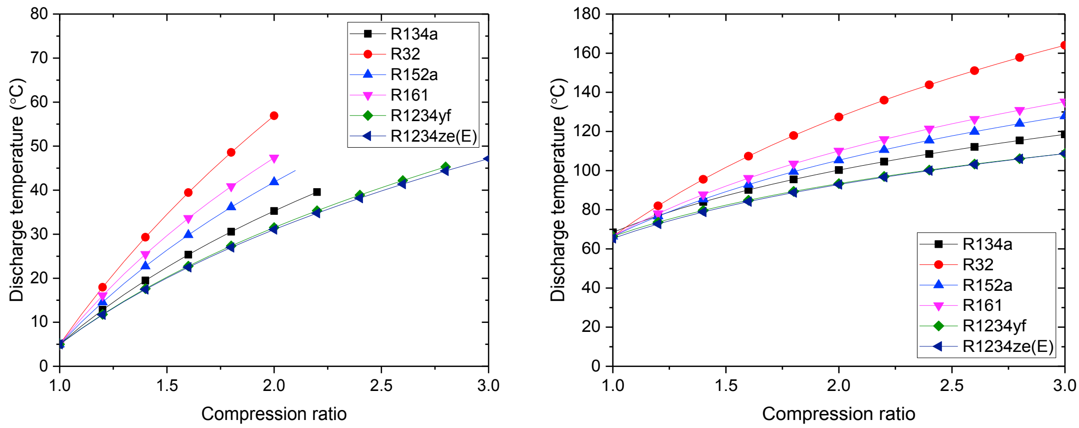
4.4. Comparison between different hybrid configurations

The COP and ECOP of the high-side hybrid cooling cycle is shown in Fig. 6. Comparing with Fig. 5, it is found that the low-side hybrid cycle has higher COPs and ECOPs than the high-side hybrid cycle. In addition, the compressor discharge temperature of low-side and high-side hybrid cooling cycles are compared in and Fig. 7. The low-side hybrid cycle yields much lower discharge temperatures than the high-side hybrid cycle. Consequently, the low-side hybrid absorption cycle is a better choice in terms of both cycle efficiency and discharge temperature.



（a）COP (b) ECOP

Fig. 6. COP and ECOP of high-side hybrid cooling cycle (T_a=T_c=30 ºC, T_e=5 ºC, T_g=70 ºC)



（a）low-side compression (b) high-side compression

Fig. 7. Comparison of discharge temperature between different hybrid configurations (T_a=T_c=30 ºC, T_e=5 ºC, T_g=70 ºC)

5. Conclusions

To facilitate better utilization of renewable/waste energy, various IL-based low-GWP working fluids were investigated for different hybrid low-temperature absorption cooling cycles. Results showed that the hybrid cycle not only greatly enhanced the COP but also lowered the generation temperature from 60~70 ºC to below 45 ºC. R32 performed the best, with a maximum COP of 0.670, while R1234yf performed the worst, with a maximum COP of 0.430. The optimal CR is 1.9~3.4 for maximum COP and 1.3~2.2 for maximum ECOP. The low-side hybrid absorption cycle is a better choice in terms of high cycle efficiency and low discharge temperature.

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