International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 307

Ideal Coefficient of Performance of Absorption Chillers and Ideal Heat-Moisture Cycle

Xiaoyue Zhang[1], Zhen Li [1*]

1 Key Laboratory of Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, PR China

ABSTRACT

Absorption heat pumps/chillers and liquid desiccant dehumidification systems are heat-moisture cycles with heat and moisture transport and conversion processes. However, previous studies mainly focused on the external performance and processes of the absorption systems. This paper provides an insight into the internal moisture transport process of the system and analyzes it from a prospective of a cycle. By considering the hygroscopic solution constraint, the expression of the ideal coefficient of performance is more precise and an ideal heat-moisture cycle working between two moisture sources at constant pressure is developed based on the analysis of the absorption chiller, which may guide the improvement of actual systems.

Keywords: heat pumps, absorption chiller, coefficient of performance, heat and mass transfer, ideal heat-moisture cycle, hygroscopic solution

NONMENCLATURE

Abbreviations	
COP	Coefficient of Performance
Symbols	
A	Absorber
C	Condenser
E	Evaporator
G	Generator

1. INTRODUCTION

Absorption heat pumps and absorption chillers use hygroscopic solutions like lithium bromide aqueous solution (LiBr-H_2O) to absorb low pressure water vapor in the evaporator. The corresponding evaporation heat is simultaneously lifted from a low temperature to a higher temperature. Thus, absorption heat pumps and chillers are commonly used for refrigeration and low-temperature waste heat recovery.

In the internal absorption chiller/heat pump, there exists a conversion between moisture and heat. The hygroscopic solution absorbs the moisture, namely the water vapor, from a lower pressure and carries it to a higher pressure while consuming high-temperature heat in the generator and rejecting low-temperature heat. So the water vapor pressure can be regarded to be compressed at the cost of thermal energy. Thus, the heat and moisture transfer and conversion cycle in the absorption heat pump/chiller is a typical heat-moisture cycle.

Previous studies focused either on the external performance of the absorption systems[1] or on the heat and moisture transfer processes in the systems[2]. Few researchers analyze the system by regarding it as a heat-moisture cycle. For a heat-work cycle, Carnot cycle is the ideal cycle that indicates the ideal efficiency of heat and work conversion, which gives guidance for thermal efficiency improvement for actual systems. However, there lacks a similar ideal cycle for heat-moisture cycles involving hygroscopic solutions.

This paper will first analyze the ideal coefficient of performance (COP) of an absorption chiller considering the internal hygroscopic solution properties. Then, an ideal heat-moisture cycle is developed based on the analyses of the ideal absorption chiller.

2. IDEAL COP OF ABSORPTION CHILLERS

2.1 Without considering hygroscopic solution constraint

Carnot cycle is the ideal heat-work cycle between two constant-temperature heat reservoirs. Similarly, in order to develop the ideal heat-moisture cycle, heat reservoir temperature and moisture source pressure should be kept constant. For an absorption chiller, the water vapor in the evaporator and condenser can be regarded as two moisture sources and their pressure is kept constant. So an absorption chiller should be analyzed before developing an ideal heat-moisture cycle.

Fig 1 shows an absorption chiller with all heat source temperature set constant. The heat source temperatures of the evaporator and generator are set as T_E and T_G, respectively, while those of the absorber and condenser are both set as T_A (which is in accordance with the actual situation as cold source generally flows into the absorber and condenser in parallel). In ideal cases, all heat transfer processes are reversible and the pump power is neglected[3].

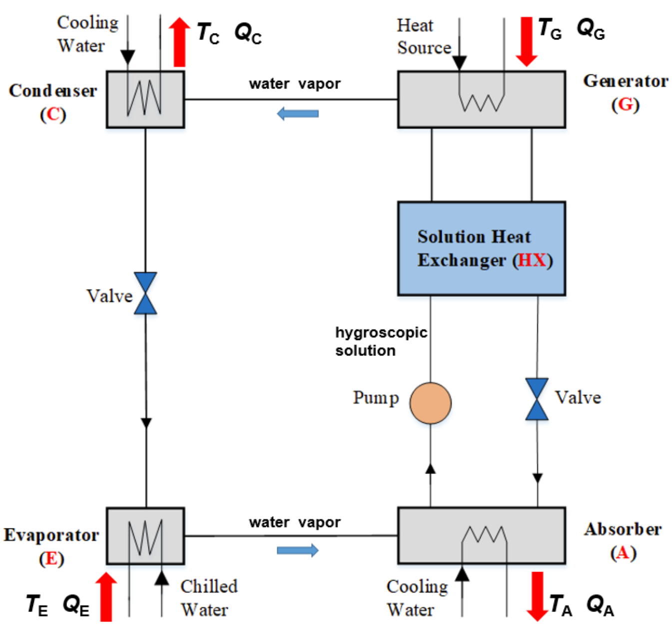

Fig 1 Absorption chiller and its heat/moisture flow

Eq. 1 and Eq. 2 show the energy conservation and Clausius inequality of the processes of the absorption chiller.

$$Q_E + Q_G - Q_A - Q_C = 0 \quad \text{(Eq.1)}$$

$$Q_E/T_E + Q_G/T_G - (Q_A + Q_C)/T_A \le 0 \quad \text{(Eq.2)}$$

Where Q_E, Q_G, Q_A, Q_C represent the absolute value of the heat exchange in the evaporator, generator, absorber and condenser. Eq. 3 can then be derived by combining Eq. 1 with Eq. 2.

$$Q_E/T_E + Q_G/T_G - Q_E/T_A - Q_G/T_A \le 0 \quad \text{(Eq.3)}$$

According to Eq. 3, the coefficient of performance of the ideal absorption chiller is:

$$\mathrm{COP_R} = Q_E/Q_G \le (T_G - T_A)/T_G \bullet T_E/(T_A - T_E) \quad \text{(Eq.4)}$$

Obviously, the upper limit of $\mathrm{COP_R}$ of the absorption chiller is the expression on the right side of the inequality sign in Eq. 4. In other words, when inequality which is the ideal COP. Current studies thus concluded that the COP of an ideal absorption refrigeration system is the product of Carnot cycle efficiency of a heat engine (working between two heat reservoirs at temperatures of T_G and T_A) and COP of a reversed Carnot cycle (working between T_A and T_E).

However, this conclusion is not accurate. For example, according to Eq. 4, the ideal $\mathrm{COP_R}$ equals 2.3 when T_A = 303 K, T_G = 363 K, T_E = 283 K, which is obviously unreasonable for a single effect absorption chiller. The reason for this problem is that the above three heat source temperatures are not independent in an ideal absorption refrigeration system: the evaporation temperature and the heat source temperature of the absorber determine the solution concentration, and the solution concentration and condensation temperature determine the heat source temperature of the generator. Therefore, the hygroscopic solution properties play a role in the absorption chiller, and the constraint from the hygroscopic solution should be considered.

2.2 Considering hygroscopic solution constraints

This section aims to add the hygroscopic solution constraints to the abovementioned equations. In ideal cases, the solution is also ideal with no heat of dilution. Ideal solution meets Raoult's law:

$$P_s = xP_w \quad \text{(Eq.5)}$$

Where P_s is the partial pressure of water vapor on the surface of the solution when the water (solvent) molar concentration is x, which is also the saturated vapor pressure of the solution since the solutes of commonly used hygroscopic solutions do not evaporate. P_W is the saturated vapor pressure of pure water at the same temperature as the solution. The saturated temperature and saturated pressure of pure water meets Clapeyron equation:

$$\ln P = A - B/T \quad \text{(Eq.6)}$$

Eq. 7 is derived based on Eq. 5 and Eq. 6:

$$\ln P_s = \ln x + A - B/T_s \quad \text{(Eq.7)}$$

Where T_s is solution temperature. According to Eq. 6, the relation between pure water saturated pressure and saturated temperature is expressed as:

$$\ln P_s = A - B/T_w \quad \text{(Eq.8)}$$

Based on Eq. 7 and Eq. 8, the relation between the saturated solution temperature T_s and pure water saturated temperature T_w under the same pressure P_s can be expressed as:

$$1/T_s = 1/T_w + \ln x/B \quad \text{(Eq.9)}$$

For the ideal absorption chiller, the constant heat source temperatures of the evaporator and condenser corresponds to the constant evaporation pressure and condensation pressure. In addition, the heat source temperatures of generator and absorber are kept constant, so the solution concentration in the absorber and generator must be kept unchanged so that the water vapor can be transferred with no pressure difference. This is the premise for a reversible process and an ideal cycle. Since the solution circulates between the absorber and the generator, a constant solution concentration means that the solution concentration in the absorber and the generator is the same. According to Eq. 9, when the solution concentration is the same, the difference between $1/T_s$ and $1/T_w$ in the absorber equals that in the generator. Thus, for the ideal absorption chiller, the relations of the heat source temperatures can be expressed as:

$$1/T_G - 1/T_C = 1/T_A - 1/T_E \quad \text{(Eq.10)}$$

Where T_A and T_C are the exothermic temperatures of absorber and condenser respectively, which are equal in this case. Eq. 10 also defines the physical constraints of solution properties on the ideal absorption chiller, indicating that the temperatures of several heat sources are not independent. By introducing equation Eq. 10 into equation Eq. 3, It can be seen that when the heat and mass transfer process in absorption refrigeration system is reversible and ideal solution is used, Q_E equals Q_G, which also conforms to the characteristic of ideal solution without dilution heat, that is, the heat absorbed and released by each component is latent heat of steam, and COP_R is 1.

In fact, the absorption refrigeration system is a system that transports water vapor from the low pressure moisture source (evaporator) to the high pressure moisture source (condenser). In the ideal case, COP_R is 1 and no energy is lost, only water vapor is transported only at the cost of reducing the grade of thermal energy (absorbing heat from the high-temperature heat source of the generator and releasing heat to the low-temperature heat source of the absorber).

3. IDEAL HEAT-MOISTURE CYCLE

The above discussion is only based on the prerequisite for the absorption refrigeration system to be reversible and ideal, but the sufficient conditions for this system to be reversible and ideal have not been clearly defined. The absorption heat pump/chiller can be regarded as a cycle in which the water vapor is transported by the hygroscopic solution from the evaporator, which is a constant moisture source at a low pressure, to the condenser, which is a constant moisture source at a high pressure. Obviously, these two moisture source pressures constitute the upper and lower boundary of the cycle. If the boundary is defined, the ideal cycle can be obtained only by ensuring that the heat and mass transfer processes of the heat and moisture cycle can be reversed. Therefore, it is necessary to ensure that there is no temperature difference in heat transfer and no pressure difference in mass transfer. In this way, the ideal heat-moisture cycle between two moisture sources (P_1 and P_2) can be constructed as follows.

The hygroscopic solution in solution reservoir A absorbs water vapor from moisture source P_1 with no driving pressure difference and releases heat to heat source T_A with no driving temperature difference; the solution in solution reservoir G absorbs heat from heat source T_G with no driving temperature difference and releases the absorbed water vapor to moisture source P_2 with no pressure difference.

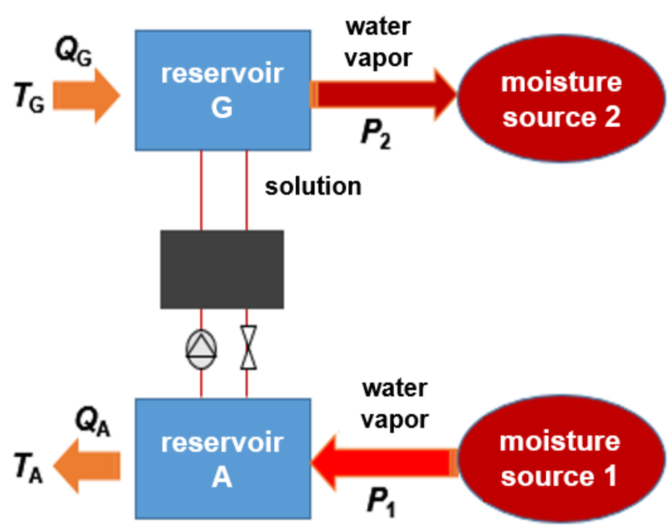

Fig 2 Ideal heat-moisture cycle

The above definition of the ideal heat-moisture cycle is abstract and simple, but it is rich in implications:

a) The moisture source and heat source are kept at constant value (pressure or temperature);

b) When the solution absorbs/releases heat to a constant temperature heat source with no temperature difference, the solution temperature is required to be unchanged, and the absorption/release of water vapor from/to the constant pressure moisture source requires the solution saturated vapor pressure to be unchanged. These requires the solution concentration to remain unchanged (the amount of water vapor absorption/release is relatively infinitesimal), and the solution concentration in solution reservoir A and solution reservoir G are the same;

c) P_1 is not necessarily smaller than P_2. When $P_1 < P_2$, the cycle is a heat-moisture cycle that absorbs high-grade heat from heat source T_G to transport moisture from a low pressure source to a higher one, such as the cycle in the absorption heat pump (AHP) and absorption chiller; When $P_1 > P_2$, the cycle is a reverse heat-moisture cycle that generates high temperature heat, such as the absorption heat transformer (AHT);

d) The above solution can also be water, i.e. infinitely dilute solution. In fact, when the solution is infinitely dilute, the above cycle is completely ideal without being affected by the actual properties of the solution.

It should be noted that the above cycle is not limited to the cycle form of an absorption heat pump as evaporator and condenser are not mentioned. Solution reservoir A and solution tank G can correspond to the absorber and generator of an absorption heat pump or the dehumidifier and regenerator of an air dehumidification system using the hygroscopic solution as working fluid. This makes the above ideal heat-moisture cycle more abstract and universal. For example, there is no evaporator and condenser in the air dehumidification system, so it is more essential and universal to replace the evaporator and condenser with two moisture sources. The two solution reservoirs are infinitely large to ensure the solution concentration is unchanged.

4. CONCLUSION

In this paper, the performance of an absorption chiller is analyzed. For an ideal absorption chiller, the hygroscopic solution constraint for the expression of COP should also be considered using Raoult's law and Clapeyron equation assuming the solution is ideal. According to the analysis, the COP of an absorption chiller is 1 when the heat source temperatures of the absorber and condenser are the same.

Further, the universal ideal heat-moisture cycle working between two moisture sources at a constant pressure is developed based on the analyses of the ideal absorption chiller. The ideal heat-moisture cycle shows the ideal system form for absorption heat pumps and air dehumidification systems using hygroscopic solutions.

ACKNOWLEDGEMENT

This research was sponsored by the National Natural Science Foundation of China (Grant No. 51776103).

REFERENCE

[1] Esfahani IJ, Lee SC, Yoo CK, Evaluation and optimization of a multi-effect evaporation–absorption heat pump desalination based conventional and advanced exergy and exergoeconomic analyses. Desalination 2015;359: 92-107.

[2] Zhang XY, Wu JD, Li Z, Irreversibility characterization and analysis of coupled heat and mass transfer processes in an absorption system. Int J Heat Mass Trans 2019;133:1121-1133.

[3] Shen WD, Tong JG, Engineering Thermodynamics. 4th ed. Beijing: Higher Education Press; 2007.