Theoretical analysis of large-temperature-difference of chilling water system

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Abstract This paper performs three absorption refrigeration cycle modes in order to achieve large temperature difference of chilling water, including single absorption cycle, two evaporators cycle and two evaporators－two absorbers cycle. The combined Carnot cycle models is established for each cycles. The COP (coefficient of performance) of ideal cycle was introduced. Quantitative analysis and comparison of each mode is investigated.

Introduction

Currently, the absorption systems are widely used in refrigeration, heating and heat recovery of industry, residential and business buildings. The urgent need is to improve the energy-saving and environment-protecting performance of absorption-cycling products. The adoption of large temperature-difference system is a new important trend. The large temperature-difference system can compensate the energy loss caused by the transportation of chilling water in district or central cooling systems. On the other hand, although the COP decreases with the increase of temperature difference, the large temperature-difference system can save transport energy by reducing the flowrate of chilling water. What is more, the initial investment of equipment is reduced because of the smaller pipe diameters of transport system. The energy saving analysis, operation characters and engineering designs of large temperature-difference systems have been discussed(Yin.P. 2000,2001)(Zhou Y.S. and Chen P.L..1999)(Huo X.P..1996). Considering the COP (coefficient of performance) of thermodynamics cycle, this paper attempt to find possible approaches to save the energy costs of large temperature-difference systems. Then some reference opinions on practical projects are given.

1 The COP of Absorption Cycle

Absorption refrigeration is based on the combined cycle of thermal engine and heat pump. Exergy, which is outputted when high-grade heat is discharged in the engine cycle, was filled into the heat pump cycle to extract part of heat from the target system at a temperature grade which is lower than the environment temperature, to a even higher temperature grade. Meanwhile the target system maintains lower temperature than the environment. Absorption refrigeration systems storage the usable work produced in the process into the cycle fluid as chemical energy. Working medium couples, as carriers, transfer and transform energy during the process of absorption/lixiviation of solution and generating/condensation of refrigerant. Therefore a reversible combined Carnot cycle drived by a heat engine is adopted to analyse the thermodynamic process of absorption refrigeration. Three modes of system achieving large temperature difference of chilling water are performed to single-action absorption refrigeration.

1.1 Mode 1（Simple absorption cycle）

In a simple absorption cycle, large temperature difference can be achieved by reducing the evaporating temperature, which can reduce supply temperature or increase the return temperature of chilling water of refrigerator. The diagrammatic sketch of practical cycles and the combined Carnot cycle are showed in Fig1. Where T_G, T_C, T_A and T_E are the temperatures of the medium in the generator, condenser, absorber and evaporator respectively, and W is the internal flow work of the medium. By modeling the Carnot engine cycle and reverse Carnot cycle, considering

$$W_a = W_1 + W_2$$

we can obtain:

$$Q_G = \frac{\left(\frac{T_A}{T_E} - 1\right)Q_E + \left(1 - \frac{T_A}{T_C}\right)Q_C}{1 - \frac{T_A}{T_G}}$$

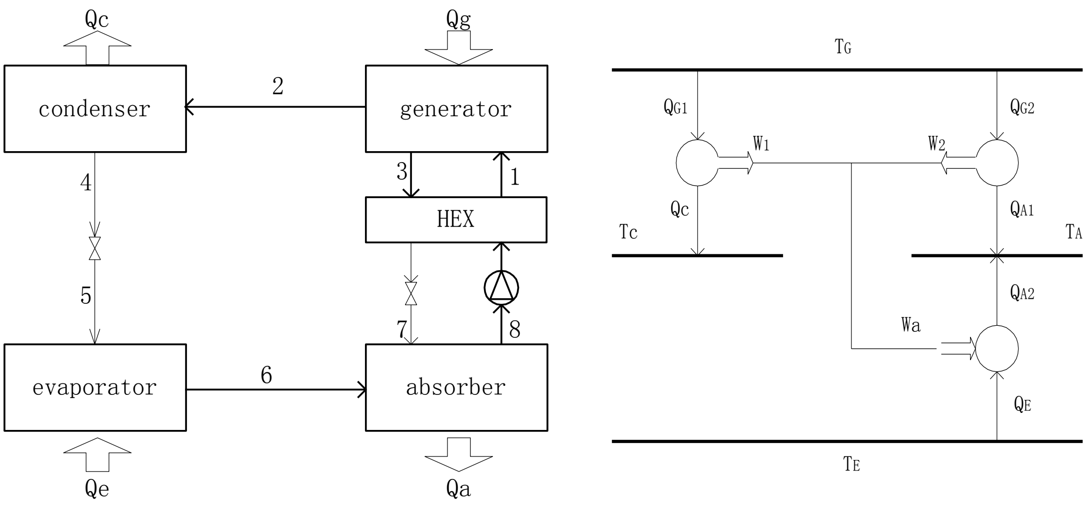

Fig 1 Simple absorption cycle and the conbined Carnot cycle

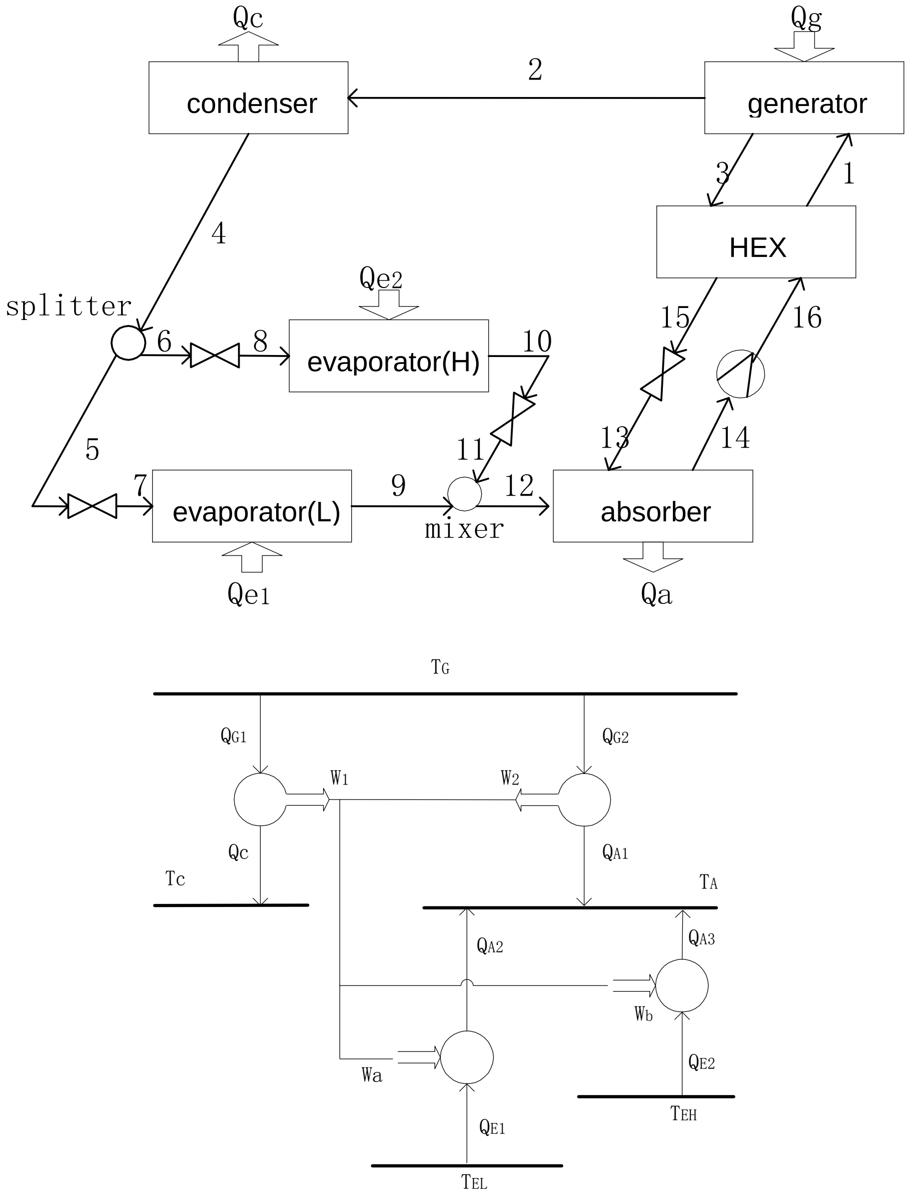

Fig2 Double-evaporator absorption cycle and the conbined Carnot cycle

Then we obtain the following equation.

$$\mathrm{COP_1} = \frac{Q_E}{Q_G} = \frac{1-\dfrac{T_A}{T_G}}{\left(\dfrac{T_A}{T_E}-1\right)+\left(1-\dfrac{T_A}{T_C}\right)\dfrac{Q_C}{Q_E}} \qquad (1)$$

1.2 Mode 2（Double-evaporator absorption cycle）

Compared to conventional absorption cycles, large temperature-difference system requires lower supply temperature or higher return temperature of chilling water. By enlarging the temperature difference, it is possible to realize stepped refrigeration at different evaporation temperatures which can reduce the irreversible loss produced by the heat transfer of chilling water and refrigerant. We can also deduce from equation (1) that COP can be reduced by reducing the evaporation temperature while can be improved by increasing the evaporation temperature. Therefore we introduce a high-temperature evaporator in mode 2. The diagrammatic sketch of double-evaporator absorption cycle and combined Carnot cycle are showed in Fig2. Where

$$K_1 = \frac{W_a}{W_b}$$

Using the same processing method as mode 1, we can obtain the following equations :

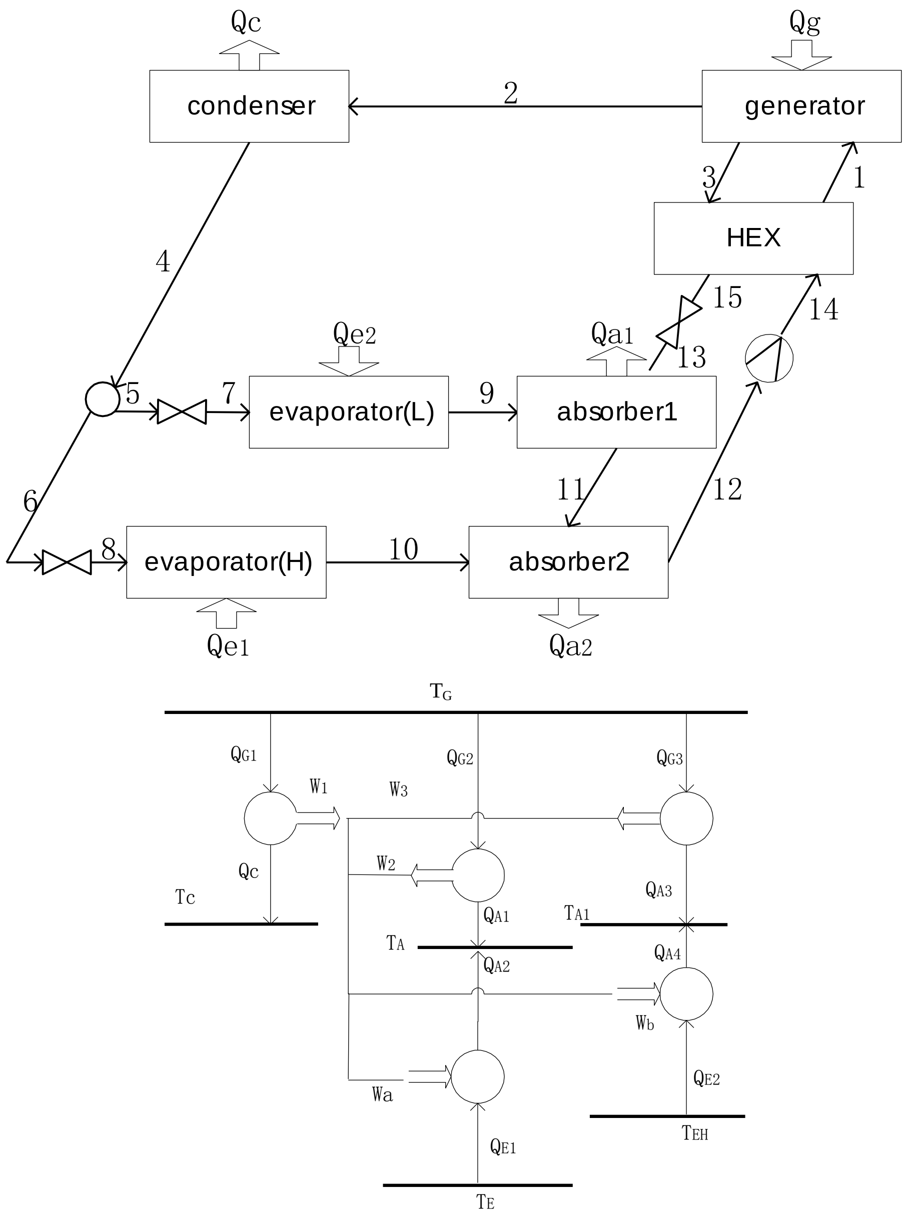

Fig 3 Double-evaporator double-absorber cycle and the conbined

$$\mathrm{COP_2} = \frac{1-\frac{T_A}{T_G}}{\frac{(1+K_1)(T_A-T_E)(T_A-T_{EH})}{K_1T_{EH}(T_A-T_E)+T_E(T_A-T_{EH})}+\left(1-\frac{T_A}{T_C}\right)\frac{Q_C}{Q_E}} \qquad (2)$$

1.3 Mode 3（Double-evaporator and double-absorber cycle）

In mode 2, the vapor of refrigerant created in the high-temperature evaporator need to be throttled in order to be utilized at a lower pressure, which cause the loss of exergy. Therefore a high-pressure absorber matching with the high-temperature evaporator is introduced based on the model of mode 2, forming a double-evaporator and double-absorber cycle. The diagrammatic sketch of double-evaporator double-absorption cycle and the combined Carnot cycle are showed in Fig3. Where

$$K_2 = \frac{W_3}{W_1}$$

By modeling the Carnot engine cycle and reverse Carnot cycle, considering

$$W_1 + W_2 + W_3 = W_a + W_b$$

we can obtain:

$$\mathrm{COP_3} = \frac{\left(1-\frac{T_A}{T_G}\right)}{\frac{(1+K_1)(T_A-T_E)(T_{A1}-T_{EH})}{K_1T_{EH}(T_A-T_E)+T_E(T_{A1}-T_{EH})}+\left[1-\frac{T_A}{T_C}+\frac{K_2(T_G-T_C)(T_{A1}-T_A)}{T_C(T_G-T_{A1})}\right]\frac{Q_C}{Q_E}} \qquad (3)$$

2 Results and discussion

2.1 Comparing mode1 to mode 2

The temperature difference of supply and return chilling water is 8~10℃ while the difference is often 5℃ in conventional air conditioning projects. Considering a central air conditioning system whose return chilling-water temperature is 17℃. To achieve a large temperature difference, the difference of supply and return chilling water temperature is set to be 8℃, therefore the supply temperature is 9℃. Accordingly the temperature of the evaporator is set to be 7℃, the temperature of absorber is 32℃ and the temperature of condenser is 42℃. Assuming that the latent phase-change heat of the refrigerant varies little with the changing of temperature, Q_C/Q_E can approximate to be 1.0. Theoretical COP of mode 1 and mode 2 can be obtained from Equation (1) and Equation (2). The theoretical COP of mode 1 and mode 2 at different K_1 and T_{EH}, the temperature of the high-temperature evaporator, are showed in Fig 4. It is seen that：

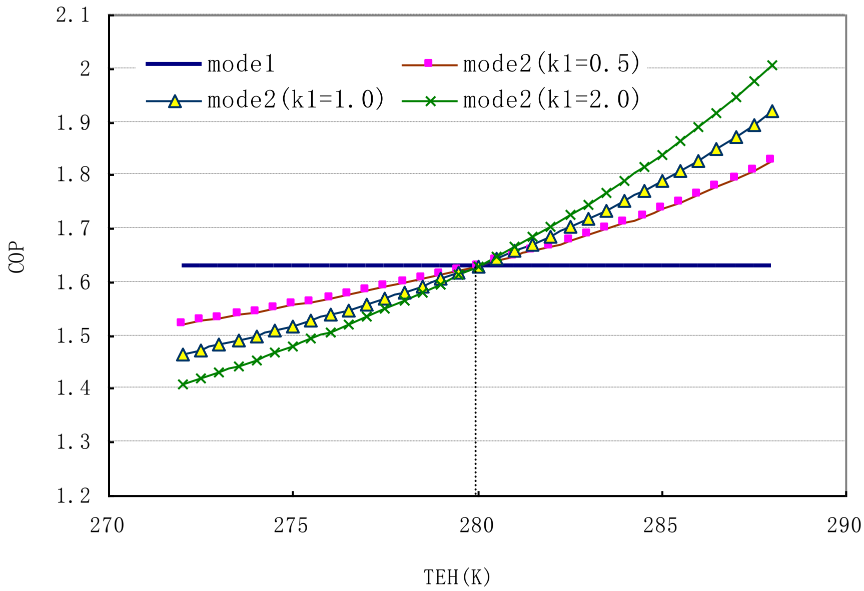

Fig 4 Comparing mode1 to mode 2

The COP increase with increasing of T_{EH};

If $T_{EH} = T_E$, then $COP_2 = COP_1$;

If $T_{EH} < T_E$, then $COP_2 < COP_1$;

If $T_{EH} > T_E$, then $COP_2 > COP_1$;

Considering Equation (2), if K_1=0, which means that the high-temperature evaporator of mode 2 is not used, the cycle of mode 2 is just the same as mode 1. When $T_{EH} < T_E$, COP fall down with the increasing of K1 while increase when $T_{EH} > T_E$. If K1 is an infinitely large quantity we can obtain the following from Equation (2):

$$COP_2 = \frac{Q_E}{Q_G} = \frac{1 - \frac{T_A}{T_G}}{\left(\frac{T_A}{T_{EH}} - 1\right) + \left(1 - \frac{T_A}{T_C}\right)\frac{Q_C}{Q_E}}$$

It is equal to the cycle of mode 2 cycle removed the low-temperature evaporator. Where

$$K_1 = \frac{\frac{T_A}{T_{EH}} - 1}{\frac{T_A}{T_E} - 1} \cdot \frac{Q_{E2}}{Q_{E1}}$$

Therefore increasing K1 means increasing the ratio of the refrigerating output of high-temperature and low-temperature evaporator. The ratio is limited by the requirement of the quality of the output. Consequently we can conclude that adopting a high-temperature evaporator in the cycle can improve the COP of the system. What is more, the mentioned above discussion is based on the theoretical reversible cycle. In practical processes, where irreversible loss exists during the heat-transfer between the chilling water and the refrigerant, adopting a high-temperature evaporator can reduce irreversible loss by reducing the mean heat-transfer temperature difference in the evaporator and thus improve the COP of the practical systems. The quantitative analysis of this problem in not included in this paper and will be discussed in the future.

2.2 Comparing mode 3 to mode 2

Based on the mode 2, a high-pressure absorber is introduced into mode 3. Where the fixed generating temperature is 107℃, the temperature of low-temperature evaporator is 7℃, the temperature of high-temperature evaporator is 11℃, the temperature of low-absorber is 32℃, the temperature of condenser is 42℃, K1 is equal to 1 and Q_C/Q_E is equal to 1.0. The COP of mode 2 and mode 3 at different temperature of absorber and different K2 are showed in Fig 5 under the conditions mentioned above. It can be seen that:

The COP decrease with the increase of T_{A1}

If $T_{A1} = T_A$, then $COP_3 = COP_2$;

If $T_{A1} > T_A$, then $COP_3 < COP_2$;

If $T_{A1} < T_A$, then $COP_3 > COP_2$;

Considering Equation (3), if $K_2=0$, which means that the high-pressure absorber of mode 3 is not used, the cycle of mode 3 is the same as mode 2. When $T_{A1} < T_A$, COP increase with the increasing of K1 while fall down when $T_{A1} > T_A$. It can be concluded that the adoption of a high-pressure absorber is favorable to improve the COP of the system when the temperature of high-pressure absorber is lower than the low-temperature absorber.

When considering the practical cycle, usable energy loss caused by irreversible mass transfer and heat transfer exist in the absorber, which complicate the problem. It can be seen from the sketch of practical absorption cycle in Fig 2 and Fig 3 that in mode 2 irreversible mass-transfer loss is created at the mass-transfer process between the high-pressure vapor and concentrated solution when the vapor of refrigerant at different pressure from the two different evaporators contacted with the homogeneous concentrated solution. While in mode 3, the mass transfer occurs at high-pressure vapor and concentrated solution of lower concentration or at low-pressure vapor and

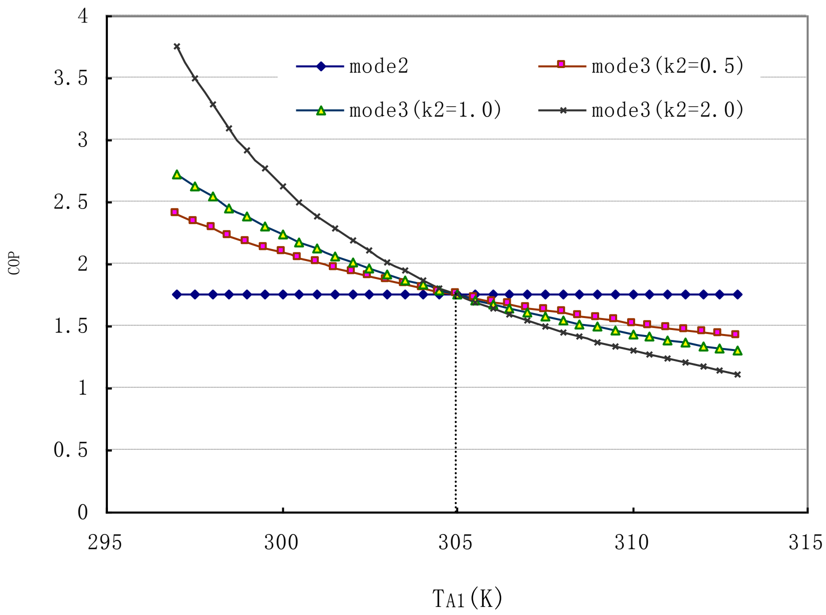

Fig 5 The comparison of mode 3 to mode 2

higher concentration solution. The mass-transfer process approximate to the countercurrent absorption in countercurrent flow, which can reduce the mass-transfer irreversible loss. Properly arranging the flow of the cooling water in the two absorbers, which can decrease the heat-transfer mean temperature difference in the absorbers, can also reduce the irreversible loss. All mentioned above are favorable to improve the COP of the system. The related quantitative analysis is not listed in this paper.

3. Conclusion

When considering the energy-saving measures of the cycle of large temperature difference, the methods such as stepped refrigeration are necessary to be involved.

（1） In mode 2, a high-temperature evaporator is added to the simple cycle and the theoretical COP is improved. In practical project, this mode can also reduce the irreversible heat-transfer loss during the evaporation process.

（2） Based on the mode 2, a high-pressure absorber is introduced in mode 3, forming a cycle with two evaporators and two absorbers. The COP of the system is improved only when the high-pressure absorption temperature is lower than the low-pressure absorption temperature. In practical system, the system with two absorbers as mode 3 is more favorable to reduce the irreversible loss than the system of mode 2.

（3） For typical double-action absorption cycle, the low-pressure generator actually equals to an inside heat regenerator to recover the heat of the vapor produced in the high-pressure generator. The ideal combined

Carnot cycle is consistent with the single-action cycle so the results and discussions mentioned above are also applicable for double-action cycles.

Reference

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