ESL-IC-06-11-211

Energy Efficiency Evaluation of Refrigeration Technologies in Combined Cooling, Heating and Power Systems

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Abstract: With development of absorption refrigeration technology, the cooling requirement can be met using various optional refrigeration technologies in a CCHP system, including compression refrigeration, steam double-effect absorption refrigeration, steam single-effect absorption refrigeration, flue gas absorption refrigeration and hot water absorption refrigeration, etc. As a universal criterion, the COP coefficient cannot reflect the difference in availability of driving energy for different chillers. Exergy efficiency of optional chillers in CCHP system was analyzed and compared, which can be regarded as an important reference criterion in comparison of energy efficiency. Furthermore, a new index, relative electricity saving ratio, was put forward for evaluating end energy efficiency of all kinds of chillers in a CCHP system, which indicates actual energy or electricity saving ratio for different absorption chillers with various parameters in contrast to the reference electricity-driven refrigeration scheme.

Key words：Combined cooling, heating and power, Energy efficiency, Absorption chillers

1. INTRODUCTION

Over the last three decades, combined heating and power (CHP) system had been accepted widely as its remarkable energy saving characteristics. CHP, the simultaneous production of electrical power and thermal power from a single fuel source, can lead to the total energy efficiency of 75~ 85%.

With increasing need for indoor comfort in summer and development of absorption refrigeration technology, combined cooling, heating and power system has attracted more and more attention. For a CHP system, its energy efficiency and economics is restricted in summer because it exists a number of surplus heat energy. A solution for achieving higher overall efficiency of CHP system is offered by exploiting the absorption chiller for cooling, which can increase remarkably heat requirement in summer.

About energy efficiency of absorption chiller, a feasibility analysis was made for district heating systems (DHSs) extends to CCHP system, comparison between the efficiency of a DHS and hot-water-driven absorption chillers for a range of hot water supply and return temperatures was made[1]. CHP system integrated with absorption chiller with different COP values is analyzed, and the thermodynamic effects are demonstrated o f integrating steam turbine-based cogeneration systems with absorption chillers [2]. Furthermore, some evaluation methods are introduced in evaluation energy efficiency of steam absorption chillers in CCHP system, including gross coal consumption rate method [3], energy consumption comparison method [4], and equivalent thermodynamic coefficient method [5].

In order to analyze and compare the energy efficiency of different chillers for waste heat utilization in CCHP system, a new evaluation index, relative electricity saving ratio (RESR) is bring forward from viewpoint of end cold energy production and electrical power consumption in this paper. Energy efficiency of steam driving absorption chiller in CCHP system is analyzed, influence of steam pressure extracted, COP of compression chiller and internal efficiency of steam turbine on RESR is compared.

2 CHOICE OF CHILLERS IN CCHP SYSTEM

Gas turbine and internal combustion engine are the most widely used prime movers in CCHP system. Based on different form of waste heat, many waste heat absorption chillers was exploited, including steam double-effect absorption chiller, steam single-effect absorption chiller, flue gas absorption chiller and hot water absorption chiller. Besides, direct-fired absorption chiller and compression chiller also can be applied in CCHP system to increase operational flexibility. There are many choice of chillers to meet cooling requirement in combined cooling, heating and power system.

For a gas turbine CCHP system, in order to provide chilled water by recovery of heat of discharged waste gas, feasible flow charts can be considered as follows.

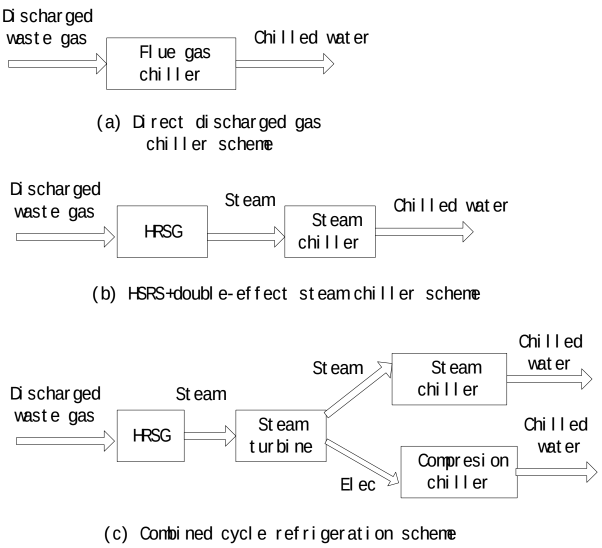


Fig. 1 Optional schemes of recovery waste gas heat for refrigeration

As can be seen from Fig 1, there are three basic refrigeration schemes for recovery gas turbine discharged waste heat. For scheme (a), discharged waste gas enters directly flue gas chiller, and chilled water is produced. For scheme (b), discharged waste gas enters heat recovery steam generator, low pressure steam from HRSG enters double-effect steam chiller for chilled water production, return water is pumped back to HRSG and heated again. Scheme (c) is a mix refrigeration flow chart which includes steam absorption chiller and compression chiller simultaneously, discharged waste gas enters heat recovery steam boiler firstly, medium or high parameters steam from HRSG enters firstly steam turbine, electrical power produced by steam turbine drive compression chiller for chilled water production, low pressure steam is extracted for steam absorption chiller. Scheme (c) selection is very flexible, steam turbine can be backpressure turbine or extraction condensing steam turbines, and the quality and quantity of extraction steam from steam turbine can be adjusted if extraction condensing steam turbine is applied.

For reciprocating engine CCHP system, it exists two different waste heat forms, engine exhaust heat and jacket coolant heat, and heat in engine jacket coolant accounts for up to 30% of energy input and is capable of producing 90-99 hot water, which can be used for single-effect absorption chiller. Compared to gas turbine, exhaust gas of internal combustion engine is low-temperature and poor, so low-pressure steam or hot water is usually generated from recovered heat used for absorption chiller, exhaust gas can also enters directly flue gas absorption chiller for chilled water generation.

3 EXERGY EFFICIENCY EVALUAITON OF DIFFERENT CHILLERS

COP coefficient is a universal criterion in evaluating efficiency of chillers, which representing the ratio of output cooling load to input energy. However, COP criterion can not reflect the difference in availability of input energy, because different chillers need various input energy including electrical power, steam, hot water or flue gas, which hold disparate absolutely energy quality.

In this paper, the exergy efficiencies for five water-cooled chillers are investigated, including double-effect steam absorption, single-effect steam absorption, double-effect flue gas absorption, compression chiller and direct-fired absorption chiller. For this analysis, the exergy of gas for direct-fired absorption chiller assumed to be its net caloric value. Exergy value of high temperature exhaust gas is calculated by equation (1), where exhaust gas is regarded as pure material and backpressure is neglected.

$$Ex = (\bar{C}p \times (T_2 - T_1) - T_0 \times \bar{C}p \times \ln\frac{T_2}{T_1})/3600 \qquad (1)$$

Where, Ex is the unit exergy value of flue gas (kWh/kg), C_p is average specific heat at constant pressure (kJ/kg.K), T_2 and T_1 (K) is gas inlet temperature and discharge temperature of chiller, respectively. T_0 is environmental temperature.

Exergy of steam can be calculated by equation 2.

$$Ex = \left[\bar{C}p \times (T_2 - T_1) - T_0 \times (\bar{C}p \times \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1})\right]/3600 \qquad (2)$$

Where, P_2 and T_2 are pressure and temperature of input steam of chiller, respectively. P_1 and T_1 are pressure and temperature of condensation water, respectively.

Cold energy exergy calculation is similar to heat energy exergy, which can be calculated by equation (1).

In this study, performance parameters for five types of chillers are shown in Table 1.

Tab. 1. Performance parameters for five types of chillers

Chiller type	Rated cold energy（kW）	COP	Chiller auxiliary power（kW）
Double-effect steam（8bar）	1740	1.35	5.25
single-effect steam（1bar）	1740	0.75	5.25
Double-effect flue gas	1740	1.35	5.25
Compression	1740	5	----
Direct fired	1740	1.35	5.25

In this calculation, environmental temperature is set as 30 , inlet and outlet temperature of chiller are set as 12 and 7 , respectively. Inlet and outlet gas temperature of Double-effect flue gas absorption chiller are set as 500 and 170 , respectively.

Exergy efficiency of five types chillers is shown in figure 2. For total refrigeration plant, extra electrical power consumption also includes chilled water pump, cooling water pump and fan of cooling tower. Exergy efficiency of five types chillers considering auxiliary equipment power consumption is also shown in figure 2.

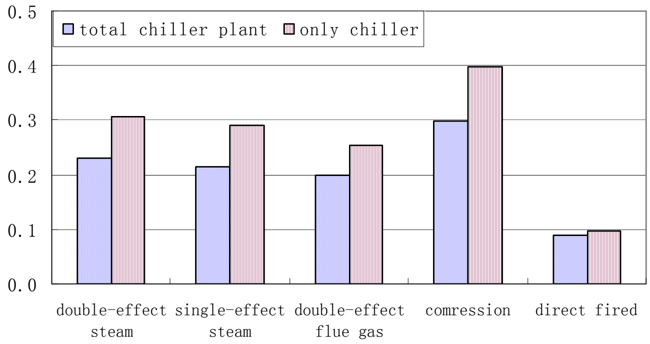


Fig 2 Exergy efficiency comparison between five types chillers

As shown from **Fig 2,** compression chiller has the highest exergy efficiency, and direct fired chiller holds the smallest exergy efficiency. If auxiliary equipment energy consumption of chiller plant is considered, the relative difference of exergy efficiency between compression chiller and absorption chiller increases because auxiliary equipment energy consumption is inverse proportional to COP of chillers.

On the other hand, exergy efficiency is only one reference index, which can't indicate actual rationality and end energy efficiency between different refrigeration mode, especially between compression and waste heat absorption chiller because irreversible loss is inevitable in transferring heat energy to electrical power. It is necessary to compare and analyze energy efficiency of different chillers applied in CCHP system, based on integrated system and end energy consumption ratio.

4 ENERGY EFFICIENCY EVALUATION OF ABSORPTION CHILLERS IN CCHP SYSTEM

For gas turbine or gas engine exhaust gas flow of given temperature, it can be compared easily which scheme shown by Fig 1 can obtain more cold energy if corresponding parameters is assumed.

Calculation indicates schemes (c) have obvious advantage over other two schemes, i.e. more cold energy can be acquired by schemes (c) based on the same exhaust gas flow.

In this paper, emphasis of analysis is focused on scheme (c). For scheme (c) shown in Fig 1, two questions will be answered.

Was steam absorption refrigeration reasonable, and did absorption chiller can improve the total refrigeration efficiency for this CCHP system?

How to define steam parameters in order to maximize cold energy production for this refrigeration scheme?

For scheme (c), it is assumed a flow of steam with heat Q_h exists which can be product by HRSG or extracted from steam turbine. It exists two basic refrigeration selections for this steam: This steam enters directly steam absorption chiller, and cold energy (Q_c) was produced at the cost of extra electrical power assumption including chiller liquid circulation pump, chilled water pump, cooling water pump and fan of cooling tower This steam enters steam turbine for electrical power production with all steam condensation, turbine can produce electrical power($w2$) for compression chiller. For this selection, extra electrical power ($w3$) will be consumed for the same quantity of cold energy (Q_c) production, and $w3$ can be positive or negative value.

Two refrigeration modes are given by Fig 3. As can be seen from Fig 3, the function of steam (Q_h) is equal to electrical power ($w2 + w3 - w1$) in order to obtain cold energy (Q_c). In this analysis, a new dimensionless parameter, relative electricity save ratio (REST) is defined, shown as equation (3).

$$RESR = \frac{w3 - w1}{w2 + w3} \tag{3}$$

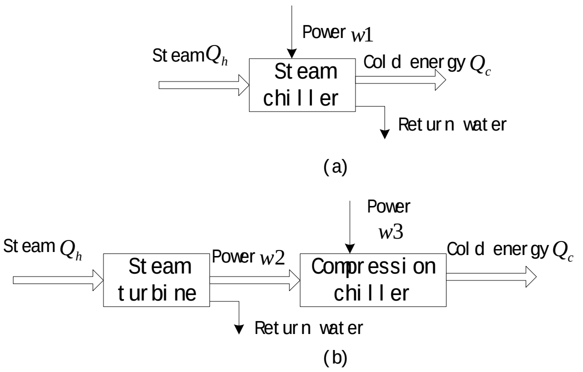


Fig 3 Two modes of steam utilization for refrigeration in CCHP system

Furthermore, equation (3) can be extended as:

$$RESR = \frac{\frac{Q_c}{COP_{elec}} - \left(G_{st}(h_i - h_{st,o})\eta_{st,i}\eta_{ge} - E_{st,tower}\right) - E_{au,ab}}{\frac{Q_c}{COP_{elec}} + E_{au,elec}}$$

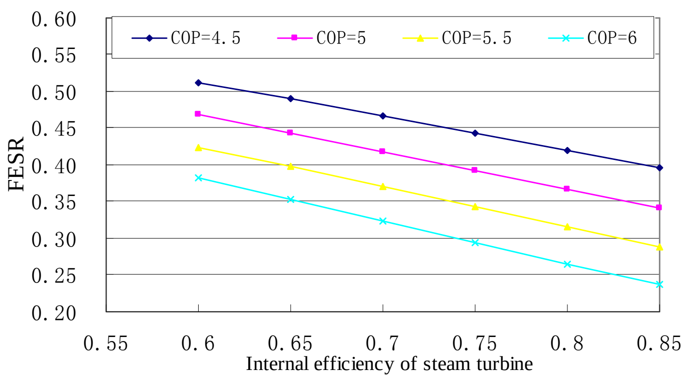
(4)

Where, COP_{elec} is COP of compression chiller selected; $E_{au,ab}$ and $E_{au,elec}$ are auxiliary power consumption of steam absorption chiller and compression chiller, respectively, both are function of COP; G_{st} is steam flow, (kg/s); h_i is enthalpy of inlet steam, (kJ/kg); $h_{st,o}$ is inlet enthalpy of steam condenser, (kJ/kg), which is function of condensation pressure; $\eta_{st,i}$ and $\eta_{st,ge}$ is internal efficiency of turbine and mechanical efficiency of electricity generator; $E_{st,tower}$ is fan power consumption of cooling tower for steam turbine.

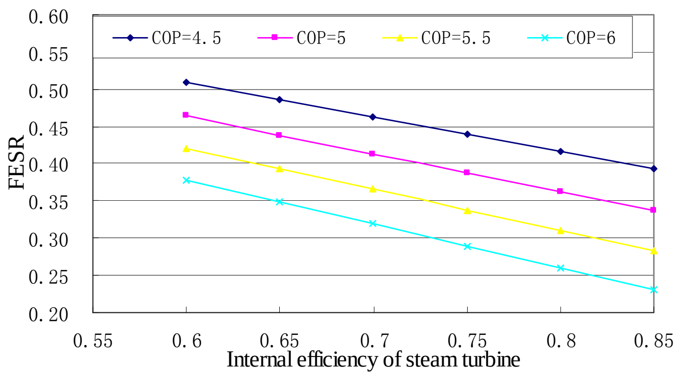
In equation (4), condensation pressure of steam condenser is set as 5kpa, $\eta_{st,ge}$ is assumed as constant 0.97. Therefore, RESR can be regarded as function of $\eta_{st,i}$, COP_{elec} and COP_{ab}, where COP_{ab} rests with inlet steam pressure P_{st} of absorption chiller. Accordingly, equation (4) can be written as shown:

$$RESR = f(\eta_{st,i}, COP_{elec}, P_{st}) \qquad (5)$$

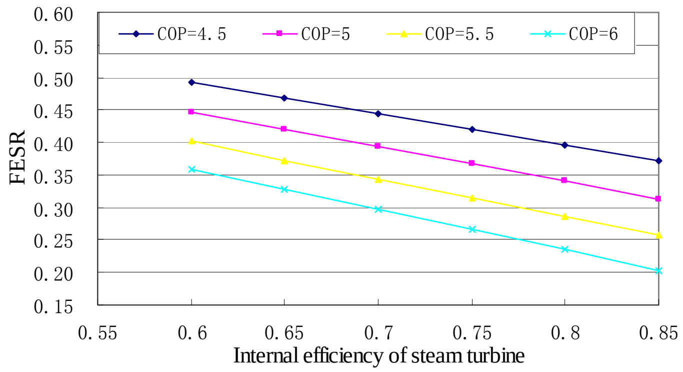
At present, steam pressure of absorption chillers holds four standard types: 8 bar (double effect, cop assumed to be 1.35), 6 bar (double effect, cop assumed to be 1.3), 4 bar (double effect, cop assumed to be 1.2), and 1 bar (single effect, cop assumed to be 0.75). Based on above four steam parameters, the relation of RESR to $\eta_{st,i}$ and COP_{elec} is computed, the results are shown as Fig 4.

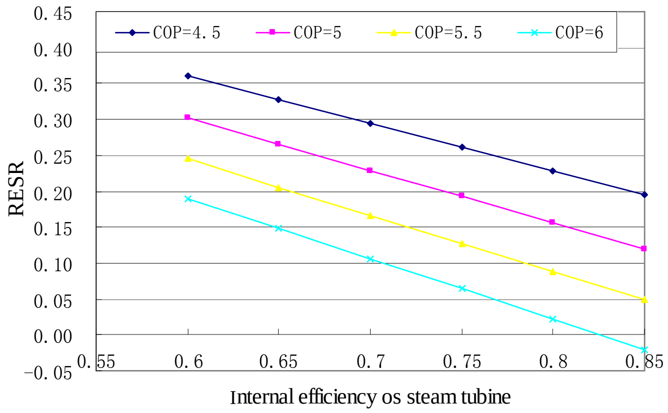


4.(a) steam pressure = 8 bar



4.(b) steam pressure = 6 bar





4.(c) steam pressure =4 bar

4.(d) steam pressure =1 bar

Fig.4 RESR changes with COP_{elec}, $\eta_{st,i}$ and steam pressure.

As can be seen from Fig 4, steam absorption chiller have obvious efficiency advantage over compression chiller for two waste heat utilization modes shown as Fig 3. RESR of double-effect steam absorption chiller compared to compression chiller is larger than 20% even if precondition is COP_{elec} =6 and $\eta_{st,i}$ =0.85. For single effect steam absorption chiller (steam pressure = 1 bar), RESR is also larger than zero in a majority of condition. On the other hand, RESR of double-effect steam absorption chiller is higher than single-effect steam absorption chiller, and RESR of chiller driven by 8 bar pressure steam is larger than that of 6 bar and 4 bar pressure steam.

About refrigeration mode for CCHP system shown in Fig 1(c), it can be concluded as follows:

a) Compared to traditional compression chiller, steam absorption chiller is a more efficient refrigeration mode if a rational CCHP system is applied, and relative electricity save ratio is larger than 20%.

b) Under permitted steam pressure of absorption chiller, higher parameters steam extracted for absorption chiller can improve total refrigeration efficiency.

5 CONCLUSION

With the development of absorption refrigeration technologies, there are many choices for cold energy production by utilizing waste heat of prime mover, including steam absorption chiller, flue gas absorption chiller, hot water absorption chiller and compression chiller. In this paper, three schemes of refrigeration for exhaust gas utilization is introduced and analyzed.

Exergy efficiency of five types chillers are compared, including Double-effect steam chiller, single-effect steam chiller, flue gas absorption chiller, compression chiller and direct fired chiller. The result indicates that compression holds the highest exergy efficiency, but higher exergy efficiency of compression chiller cannot represent higher end energy efficiency when exhaust gas heat is used for cold energy production in CCHP system, because irreversible loss is inevitable in transferring energy.

For refrigeration mode selection in CCHP system, a new index, relative energy saving ratio was put forward in evaluating end cold energy production efficiency for waste heat utilization. The results show that absorption chiller driven by steam extraction from turbine is more efficient compared to compression chiller driven by electricity produced by steam turbine, if rational parameters of steam is established. Besides, higher parameters steam extracted from turbine for absorption chiller can usually improve total cold energy generation efficiency under permitted pressure of absorption chiller.

REFERNCES

[1] A Kitanovski, A Poredos. Efficiency of a district heating network serving hot water absorption chillers. Proceedings of the Institution of Mechanical Engineers -- Part A -- Journal of Power & Energy, 2001, 215: 185-189

[2] R Tang, M. A. Rosen. Integrated systems for cogeneration and absorption chilling: comprasion for varying chiller COPs. Proceedings of the ASME Advanced Energy System Division, 1999, 661-669.

[3] Fu Lin; Jiang Yi. Thermodynamic Economic Analysis of Heating, Electricity and Refrigeration Triple-generation System from the Viewpoint of a Gross Coal Consumption Rate. Journal of Engineering for Thermal Energy and Power, 1999， 14(1):10-13.(In Chinese)

[4] Yan DeLong, Zhang WeiJun. Integrated energy conservation condition for CCHP system. China Energy, 1996,4:29-33. (In Chinese)

[5] Yang SiWen, Developing combined cooling, heating and power system, popularizing absorption refrigeration technologies. Factory Power, 1993(2):12-18. (In Chinese)