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Analysis of gas turbine inlet cooling system based on double-effect lithium bromide absorption chiller

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Abstract: *The study analyzes the theoretical gain of the gas turbine inlet cooling system using a single absorption double-effect lithium bromide chiller based on real climatic data and gas turbine technical parameters, and through rational logical analysis and calculations, using the annual fuel savings ΣB as the criteria. The calculation uses the technical parameters of UGT 10000 (NISO =10.5 MW) to derive the optimal design value and the corresponding gain of the intake air cooling system. The results show a fuel saving of 26,359.2 g per 1 kW power output of the unit in year-round operation, for a total annual fuel saving of 354.6 t.*

Keywords: *gas turbine air cooling system; cooling load; cooling capacity; annual fuel reduction*

1. Introduction

Gas turbine combined cycle (GTCC) is an efficient way to generate electricity with a thermal efficiency of up to 55% or more and is considered as one of the best options to generate electricity from fossil energy sources in the coming decades. The unit operating efficiency and power output of gas turbines are largely influenced by the inlet air temperature[1], and for every 10°C increase in the inlet gas temperature, the specific fuel consumption will increase by 1.5% to 4% [2]. Therefore, the use of exhaust gas waste heat driven inlet cooling system is a promising and practical research direction.

2. Literature Review

Hamed Sadighi Dizaji et al. designed an inlet air cooling system with integrated Maisotsenko-cycle and absorption chiller, where the air is first cooled to dew point temperature by the M-cycle and then passed into the absorption chiller for further cooling. This system requires far less cooling capacity to cool the air to the gas turbine's design intake temperature of ISO condition (15°C, 100% RH) than conventional intake cooling solutions. In some specific cases the reduction to the design value of 15°C can be achieved with M-cycle alone, reducing the cooling requirement by up to 92% [3].

Andrii Radchenko et al. proposed an innovative cooling system design for temperate climates: inlet air cooling is implemented in two stages depending on the cooling temperature. The solution is divided into a high temperature cooling stage and a low temperature cooling stage. The results of the study showed that the annual fuel savings of a combustion turbine using a combined absorption-injection inlet cooling system is 50% higher than that of a combustion turbine using only an absorption single-effect lithium bromide chiller system[4].

Absorption chillers are widely used by inlet air cooling system in oil and gas industry[5]. Absorption double-effect lithium bromide chillers have a higher energy efficiency ratio (COP=1.1-1.3) than the widely used single-effect lithium bromide chillers (COP=0.6-0.7), and can use a high-grade heat source, i.e., they can be driven directly by combustion engine exhaust gas. Therefore, it is very reasonable to use exhaust gas-driven absorption double-effect lithium bromide refrigeration unit as an intake air cooling system.

The study analyzed the energy savings of inlet cooling system using dual-effect lithium bromide chiller based on real meteorological data and gas turbine technical parameters by using a reasonable calculation method [4].

3. Materials and Methods

Air temperature tamb , relative humidity φamb and absolute humidity damb are important input parameters in the analysis process. The monthly average temperature and relative humidity for the whole year 2021 in Shanghai, China were obtained from 'meteomanz' and the time distribution of the year requiring TIAC participation was analyzed on a monthly basis. Assuming that the air temperature is reduced by ACh (absorption lithium-bromide chillers) to the design inlet temperature of most gas turbines t_0= 15°C, the incoming air temperature reduction $\Delta t = t_{amb} - t_0$.

Cooling capacity of TIAC (turbine inlet air cooling) system

$$Q_0 = c - k - \Delta t - G_a, kW \tag{1}$$

where c is the specific heat of moist air, κ is the adiabatic heat capacity ratio of air, and G_a is the air flow rate in kg/s. The value of Q_0 reflects the cooling capacity required by the TIAC to cool the ambient air to a target temperature of t_0= 15°C. When $\Delta t \leq 0$ indicates that the ambient temperature is less than or equal to 15°C, i.e. the unit operates without TIAC participation, then G_a= 0. To simplify the calculation and make the results more generalizable, introduce

$$q_0 = c - k - \Delta t = Q_0/G_a \, , kW/(kg/s) \tag{2}$$

the cooling capacity when the air flow rate Ga = 1 kg/s.

CDH (cooling degree hours) is a widely used metric by the cooling industry for calculating cooling loads and for participating in energy-related calculations [6,7]. Cooling load

$$CDH = \Delta t - \tau, K \cdot h$$

τ is the duration. This results in the annual cooling load

$$\sum CDH = \sum(\Delta t - \tau) \, , K \cdot h \tag{3}$$

The value is the accumulation of the current cooling load (CDH). In this study, CDH is calculated for each month, and $\sum$ CDH is the accumulation of the cooling load for each month of the year.

Fuel savings B is used as a criterion to evaluate the energy saving benefits in studies of gas turbine inlet cooling systems, and it's value depends on the cooling load CDH [8], the reduction in fuel per 1°C reduction in inlet air temperature and the gas turbine output, using the equation

$$B = CDH - \Delta b_e \cdot P, g \tag{4}$$

to calculate. The constant $P(N_{eISO})$ is the total output power of the gas turbine, and the constant Δb_e can be regarded as one of the performance parameters of the gas turbine, indicating the reduction in fuel consumption B, g under the operation of the maintenance power P for each 1°C decrease in the inlet air temperature[7]. or to simplify the calculation and generalize the results, use

$$b = CDH - \Delta b_e = B/P \, , g/kW \tag{5}$$

to calculate the amount of fuel saved per 1kW output of the unit when the TIAC cools the air to the target temperature t_0 = 15°C.

In order to calculate the maximum energy efficiency gain of the inlet cooling system, it is necessary to establish $\sum b = f(q_0)$ to analyze the trend of the total fuel savings $\sum$ b of TIAC with the cooling capacity q_0 to obtain the value of the total annual fuel savings $\sum$ b corresponding to the cooling capacity q_0 ; at the same time, in order to make the results have the reference value for practical application and avoid over-designing the TIAC system cooling capacity and thus using too much exhaust gas from the combustion engine, which further reduces the exhaust gas to the waste heat boiler and causes a reduction in the unit operating efficiency[9], it is necessary to establish $\sum b / q_0 = f(q_0)$ to determine the optimal TIAC design cooling capacity q_{dsgn} [4,10], i.e., the cooling capacity corresponding to the maximum annual fuel savings increment $\sum b / q_0$ (max); at the optimal design cooling capacity q_{dsgn} the TIAC system will avoid thermal energy waste; the maximum specific annual fuel savings $\sum b_m = f(q_{dsgn})$ with practical reference value can be calculated after determining the optimal design cooling capacity.

4. Results

GTCC units using absorption dual-effect lithium bromide chiller inlet cooling systems use a single chiller, where the ambient air is cooled by the ACh to reach the chiller outlet at t_0 = 15°C and then enters the compressor to be compressed and passed to the combustion chamber. The heat required for the TIAC is provided by the exhaust gas from the turbine, which is passed partly to the waste heat boiler to generate steam to drive the steam turbine and partly to the TIAC drives an absorption chiller for intake air cooling (Figure 1).

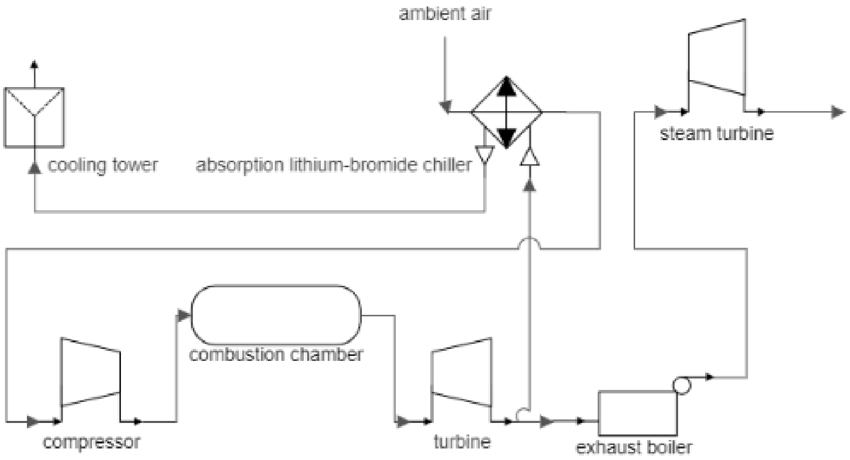


Figure 1: A scheme of GTCC TIAC system with double-effect ACh

The large fluctuations of air temperature t_{amb} throughout the year imply that the load of the TIAC system varies widely at different time periods. In order to calculate the cooling demand throughout the year, design a reasonable cooling capacity of the TIAC system, and evaluate the energy efficiency benefit of GTCC using TIAC system, the annual temperature distribution needs to be analyzed to determine the coverage time of TIAC system operation (Figure 2).

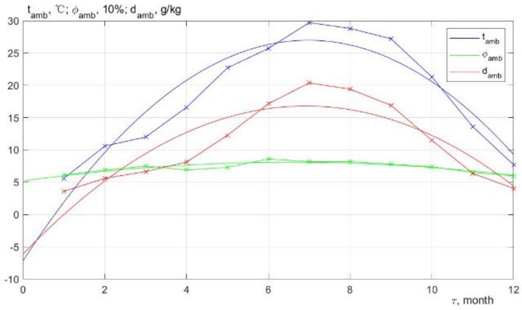


Figure 2: Climatic condition during 2021 in Shanghai, China

Based on the temperature distribution obtained from Figure 2 and the TIAC system operating coverage time, the unit flow cooling capacity q_0 required for the TIAC system to cool the ambient air temperature to t_0 = 15°C can be calculated (Figure 3).

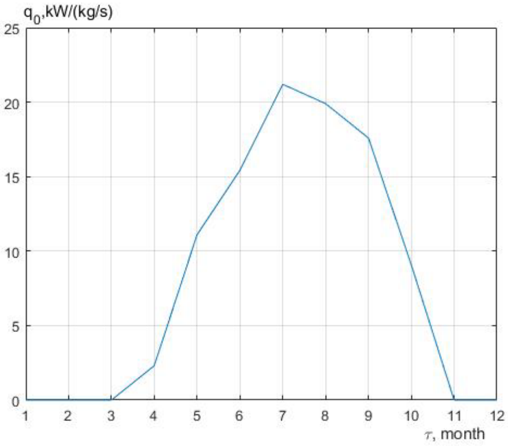


Figure 3: Specific cooling capacity

Figure 3 shows that the cooling load of the TIAC system varies significantly, which requires that the TIAC be properly sized to accommodate the changing cooling demand.

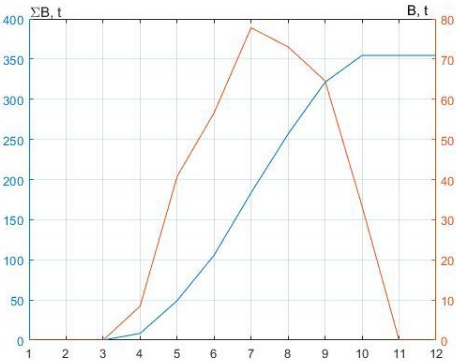
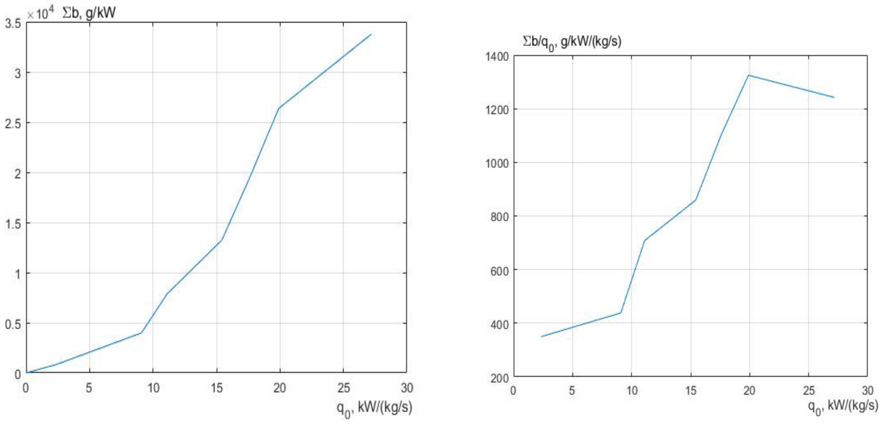


Figure 4: Annual fuel reduction ΣB and fuel reduction B (monthly)

The fuel savings with the TIAC system are significant. figure 4 and subsequent calculations assume a UGT 10000 gas turbine with output power P(N_{ISO})= 10.5 MW and fuel savings Δb_e = 0.7 g/(kW·h) for every 1 K reduction in intake air temperature. The highest temperature period of the year saves 77.8 t of fuel, and the theoretical maximum cumulative fuel savings for the year is 354.6 t.

The theoretical maximum annual fuel savings can reflect the great potential of TIAC systems in terms of energy saving, but it lacks reference value in practical applications. If the TIAC units are designed according to the maximum cooling capacity by considering only the gain of inlet air cooling, it will result in oversized units and excessive thermal energy consumption, resulting in a huge waste of resources and thermal energy. Therefore, it is also necessary to calculate reasonable design values, and the conclusions obtained under reasonable design values are more informative.

In order to derive reasonable design values and the corresponding fuel savings, graphs of $\sum \mathrm{b} = \mathrm{f}(q_0)$ and $\sum b/q_0 = \mathrm{f}(q_0)$ (Figure 5) need to be further analyzed.

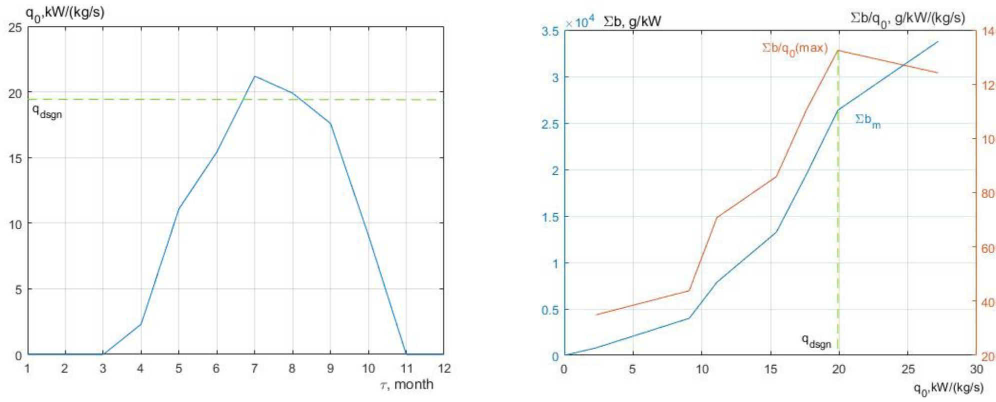


(a) *(b)*

Figure 5: Total specific fuel reduction $\sum b$ versus specific cooling capacity q_0 and total specific fuel reduction relative increment rate $\sum b\ /q_0$ versus specific cooling capacity q_0

As the design cooling capacity q_0 increases, the fuel savings increase, but the rate of increase begins to decrease near the maximum value, indicating that the efficiency of the TIAC system with excess design cooling capacity begins to decrease. The design cooling capacity q_{dsgn} corresponding to the maximum rate of fuel savings growth can be considered as the design value having the highest efficiency, while the optimal design value qdsgn corresponding to $\sum \mathrm{b}_m$ is considered as the annual specific fuel savings with practical reference value (Figure 6).

In the case of UGT 10000 (NISO =10.5 WM), the maximum relative fuel savings growth rate $\sum \mathrm{b}\ /\mathrm{q}_0$ (max) corresponds to the optimal design value q_{dsgn}=19.9 kW (kg/s) for 85.7% of the annual cooling requirement (Figure 6.a), at which the TIAC system can be kept operating at the highest energy efficiency, corresponding to an annual The fuel savings Σbm = 26359.2 g/kW.



(a) (b)

Figure 6: Rational design value of cooling capacity qdsgn and corresponding relative increment $\sum b/q_0$ *(max), fuel reduction* $\sum b_m$

5. Conclusions

Obtain the monthly average temperature and relative humidity of Shanghai for the year 2021, analyze the temperature distribution to determine the cooling demand and design cooling capacity; take the UGT 10000 gas turbine as an example, in order to adapt to the changing cooling load throughout the year and maximize the energy utilization efficiency, a reasonable design value qdsgn for the cooling capacity of the TIAC system is determined by analyzing $\sum \mathrm{b} = \mathrm{f}(q_0)$ and $\sum b/q_0 = f(q_0)$; by The optimal design value q_{dsgn} can be used to derive the benefits of the TIAC system: 26359.2 g of fuel can be saved for every 1 kW of power output of the unit operating throughout the year, and the total annual fuel savings amount to 354.6 t.

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