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ANALYTICAL INVESTIGATION OF THE PERFORMANCE PARAMETERS OF MARINE GAS TURBINE EQUIPPED WITH EVAPORATIVE COOLERS

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The gas turbine is considered as an effective equipment in ships, however, its higher intake temperature is a defect. Herein, the effect of evaporative cooling intake system for marine gas turbine is analyzed, and formulas for calculating the performance parameters of marine gas turbine with and without evaporative cooling intake system are given. Taking the Baltic Sea voyage as an example, it is proved that the evaporative cooling intake system is beneficial. In a word, our finding may provide references for the users of marine gas turbine to choose the cooling mode of intake air.

Keywords: Evaporative cooling intake system; Inlet temperature; Moisture content; Correction factor

1. Introduction

Marine gas turbine is an important power plant on modern ships. It has the advantages of large specific power, small volume, compact structure and low noise [1]. On the military side, the current frigates, especially the large-scale frigates equipped with modern weapons, are increasingly driven by gas turbines. Moreover, gas turbines will replace steam engines as power units in destroyers and cruisers. Light aircraft carriers also tend to be driven by gas turbines. In the field of civil ships, gas turbine has been widely used in high-speed ferries, large tourist ships and merchant ships in recent ten years [2]. However, as a volumetric power machine [3], the output of the gas turbine depends on the inlet mass flow rate largely. When the inlet temperature is decreased, the mass follow rate is increased, and then the output and efficiency of the gas turbine are also enhanced [4]. So it is the main method to maintain the high output and high efficiency of gas turbine by installing the compressor inlet cooling system to keep it running at low inlet temperature all the year round [5].

Evaporative coolers first appeared in the world in the late 1980s [6]. Chaker M. analysed the intake parameters of the evaporative cooling system, which required continuous analysis to determine the limit of evaporative cooling [7]. Through literature review and thermal simulation examples, Carmona J.

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established a tool to evaluate the effect of evaporative cooling on an existing simple cycle General Electric Frame 9E performance in 2015, and the potential benefits of evaporative cooling in coastal areas were presented [8]. In 2017, Baakeem S.S.et al. took a typical 42-MW gas turbine unit as the research object, and researched the difference of thermal efficiency and fuel consumption among cities under standard and actual conditions [9,10].

Direct evaporative cooling is realized by the exchange of heat and moisture between water and air. In the absence of other heat sources, the air transfers sensible heat to water, then the temperature of air reduces. The moisture content of the air is increased due to the evaporation of water. Besides, the water evaporates into the air and brings back some latent heat of evaporation. These two types of heat are equal, so the water temperature will be stabilized at a balanced temperature, which is the wet bulb temperature of the air [11,12]. And this process in psychrometric chart is an isenthalpic process, which is shown in Fig. 1. In the direct evaporative cooling process, the temperature is lowered and the moisture content is increased. The lowest temperature that can be reached by the treated air is the wet bulb temperature of the air (point 3 in Fig. 1). Because the cooling process requires constant replenishment and the amount of water that the air can contact is not infinite, the circulating water temperature is generally higher than the wet bulb temperature. In other words, the treated air temperature (point 2 in Fig. 1) cannot reach the wet bulb temperature [13]. Therefore, the performance of direct evaporative cooling can be evaluated according to the ratio of cooling degree in the actual process and the maximum degree of cooling capacity in the ideal process, that is:

$$\eta = (t_1 - t_2)/(t_1 - t_s). \quad (1)$$

in Eq. (1): η-- Direct evaporative cooling efficiency, t_1-- Air temperature before evaporative cooling, t_2-- Air temperature after evaporative cooling, t_s-- Wet bulb temperature of air.

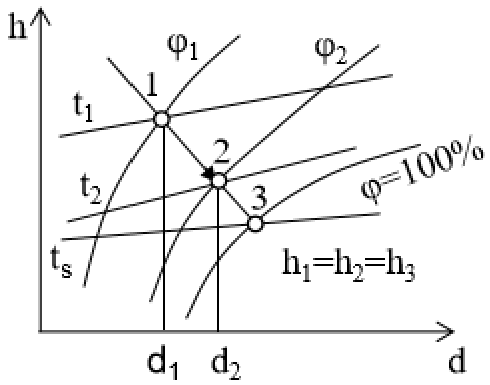

Fig. 1. Process of direct evaporative cooling on psychrometric chart

In this paper, the formulas for calculating the performance parameters of marine gas turbine with and without evaporative cooling intake system are both given. It is proved that the evaporative cooling intake system for marine gas turbine is effective by taking the Baltic Sea voyage as an example.

2. Description of the System and Working Principle

A simple gas turbine cycle consists of three basic components: compressor, combustion chamber and gas turbine. The schematic of a simple gas turbine configuration with evaporative cooling intake system is shown in the Fig. 2, in which the evaporative cooling intake system consists of wet curtain, water distributor and water tank, etc. Its detail is shown in Fig. 3: water enters through the inlet of the water pump. The water pump is conducive to the continuous circulation of water to overcome all kinds of resistance (gravity), and the direction, flow and speed of the water are adjusted through valve a. Flowmeter A measures water flow. The incoming water reaches the shower box assembly, which is composed of the water distribution box and the water distribution pipe. The water in the water distribution box flows evenly into the water curtain through the water distribution pipe, forms a water film on the surface of the curtain, and exchanges heat and humidity with the incoming filtered air. Because the water temperature is lower than the air, part of the cooling water evaporates into steam, then the remaining water returns to the tank and is discharged through valve b and drain pipes for other purposes. The loss of sensible heat in the air lowers the temperature, and some water vapor enters the air and mixes with it to increase the relative humidity of the air [14].

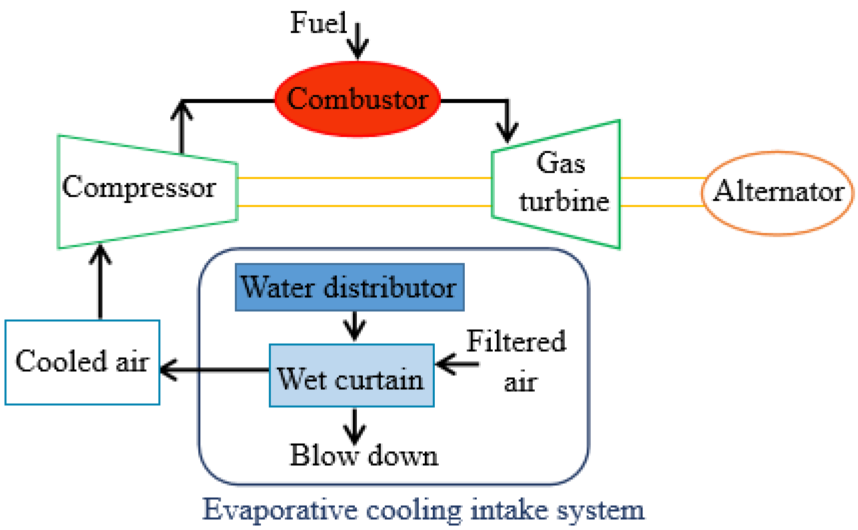

Fig. 2. Schematic of a simple gas turbine configuration with evaporative cooling intake system

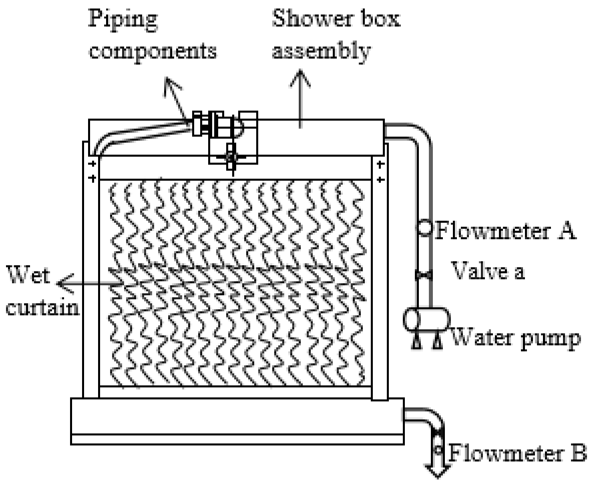

Fig. 3. Detail drawing of the evaporative cooling intake system

Fig. 4. GLASdek packing of the wet curtain

The wet curtain in the system is filled with GLASdek packing, as shown in Fig. 4, with a thickness of 300 mm. In addition, the main accessories materials of the system are stainless steel and PVC (Polyvinylchlorid) pipe fittings, which do not worry about corrosion.

3. Influencing Factors of Marine Gas Turbine Evaporative Cooling Intake System

In this paper, the effects of inlet temperature, air relative humidity, intake resistance loss on the efficiency of marine gas turbine are considered.

According to the thermodynamic cycle characteristics of the gas turbine, the efficiency of gas turbine is affected by atmospheric temperature, which is increased with the decrease of atmospheric temperature [15,16]. The relationship between atmospheric temperature and gas turbine performance parameters is shown in Fig. 5, in which correction factor is the ratio of performance parameter of gas turbine at non-standard air inlet temperature to gas turbine performance parameter at standard air inlet temperature.

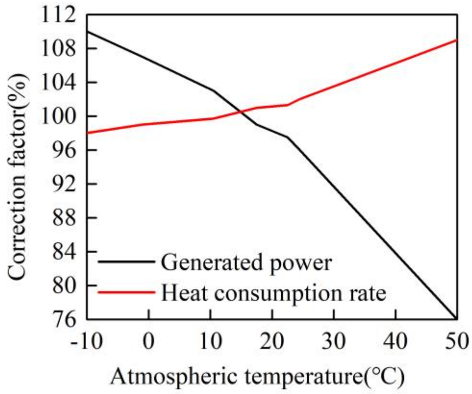

Fig. 5. Relationship between performance parameters of gas turbine and atmospheric temperature

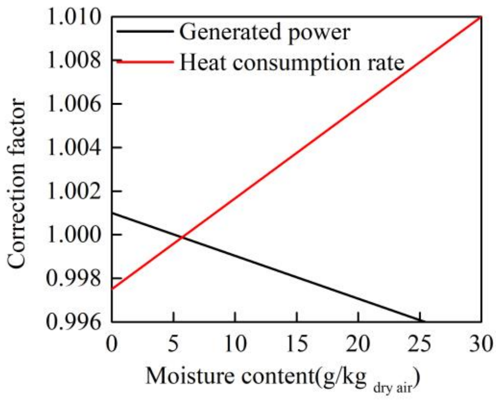

Fig. 6. Relationship between gas turbine performance parameters and intake moisture content

Due to the presence of relative humidity, there will be water vapor in the combustor. The evaporization of water vapor in the combustion process will result in a decrease in the outlet temperature and pressure of compressor, which will cause the efficiency of the gas turbine to change. In general, as the relative humidity of inlet air increases, the efficiency of gas turbine will decrease [17,18]. The relationship between the moisture content of inlet air (the mass of water in 1kg dry air) and the performance parameters of gas turbine is shown in Fig. 6.

The effect of intake pressure loss on the operation efficiency of gas turbine: when the intake pressure loss increases by 10.0 kPa, the output will decrease by 1.5% and the heat consumption rate will increase by 0.5% [19].

4. Model Establishment and Calculation Method

The modeling method adopted in this paper is similar to that in references [20,21]. As shown in Fig. 7, taking wet curtain in the system as the calculation area to establish the model. According to the working principle of system, the processing of evaporative cooling between water and air occurs on the surface of wet curtain. That is to say, the air in front of the wet curtain is the inlet air before installing the evaporative cooling intake system, the temperature and moisture content of which are denoted by t_1 and d_1 , respectively; While the air behind the wet curtain is the inlet air of gas turbine with evaporative cooling intake system, the temperature and moisture content of which are expressed by t_2 and d_2, respectively.

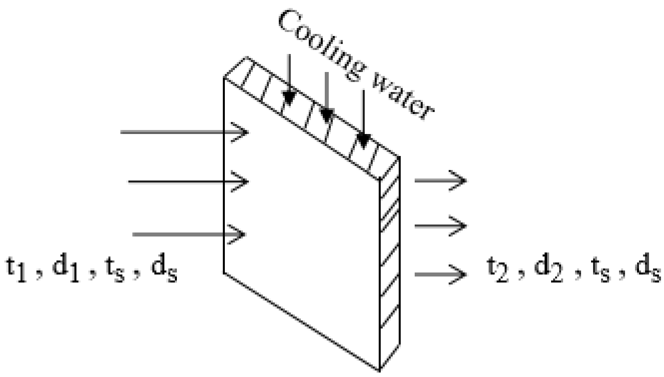

Fig. 7. Schematic diagram of direct evaporative cooling model

According to the relationship between evaporative cooling efficiency and the temperature before and after cooling, which is given by Eq. (2), the temperature after cooling can be expressed as the following formula:

$$t_2 = t_1 - (\eta/100\%) \times (t_1 - t_s) \tag{2}$$

in which, the value of η is 0.85

Similarly, the moisture content of the outlet air d_2 is expressed as Eq. (3):

$$d_2 = d_1 - (\eta/100\%) \times (d_1 - d_s) \tag{3}$$

where d_1 and d_s are moisture content corresponding to inlet air temperature and inlet wet bulb temperature of the system respectively.

For gas turbine without evaporative cooling intake system, the annual power generation of it is calculated from Eq. (4):

$$P_1 = \sum_{j=1}^{12} P_{aj} = \sum_{j=1}^{12}\sum_{i=1}^{Tj} P_{ia} = \sum_{j=1}^{12}\sum_{i=1}^{Tj} (l_{tai} l_{sai} P) \tag{4}$$

where P_1 and P_{aj} are the total energy generation for one year and generation in the j-th month of the gas turbine; P_{ia} is the power generation of the gas turbine at the i-th hour; T_j is the total number of hours in the *j*-th month; P is the output of the gas turbine under standard operating condition, l_{tai} and l_{sai} are correction factors of the inlet temperature and moisture content to the output of the *i*-th hour, which are obtained by Fig. 5 and Fig. 6 respectively.

The annual heat consumption of gas turbine can be calculated as follows:

$$Q_1 = \sum_{j=1}^{12} q_{aj} = \sum_{j=1}^{12}\sum_{i=1}^{Tj} (P_{ia} q_{ia}) = \sum_{j=1}^{12}\sum_{i=1}^{T_j} [P_{ia}(\xi_{tai}\xi_{sai} q)] \tag{5}$$

where Q_1 and q_{aj} are heat consumption of gas turbine without inlet evaporative cooling system installed for one year and heat consumption of gas turbine in the *j*-th month respectively; q_{ia} is the heat consumption rate of gas turbine in the *i*-th hour; q is heat consumption rate of gas turbine under standard operating conditions; ξ_{tai} and ξ_{sai} are correction factors of the inlet temperature and moisture content to the heat consumption of the gas turbine without evaporative cooling system of the i-th hour, which are obtained by Fig. 5 and Fig. 6 respectively.

The average output per hour and average heat consumption per hour can be calculated by using the relationship of $\overline{P_1} = P_1/8760$ and $\overline{Q_1} = Q_1/8760$ respectively.

For gas turbine with evaporative cooling intake system, the annual generation of gas turbine is calculated by Eq. (6):

$$P_2 = \varphi_P P_1 + (\sum_{j=1}^{n} P_{bj} - \varphi_p \sum_{j=1}^{n} P_{aj}) \tag{6}$$

where n is the total number of months per year in which the evaporative cooling system is operation; P_2 is the energy generation of gas turbine for one year after installing the evaporative cooling system; P_{bj} is the energy generation of the gas turbine at the j-th month,which is expressed by Eq. (7); φ_p is correction coefficient of output affected by intake pressure loss.

$$P_{bj} = \sum_{i=1}^{T_j} P_{ib} = \sum_{i=1}^{T_j} (\varphi_p l_{tbi} l_{sbi} P) \tag{7}$$

where P_{ib} is the power generation of the gas turbine at the i-th hour; l_{tbi} and l_{sbi} are correction factors of the outlet temperature and moisture content to the output of the gas turbine with evaporative cooling system of the i-th hour, which are obtained by Fig.5 and Fig.6 respectively.

The annual heat consumption of gas turbine is calculated from Eq. (8):

$$Q_2 = \varphi_p \varphi_q Q_1 + (\sum_{j=1}^{n} P_{bj} q_{bj} - \varphi_p \varphi_q \sum_{j=1}^{n} p_{aj} q_{aj}) \tag{8}$$

where Q_1 and q_{bj} are heat consumption of gas turbine with inlet evaporative cooling system installed for one year and heat consumption of gas turbine in the j-th month respectively. φ_q is correction coefficient of heat consumption affected by intake pressure loss. The q_{bj} is given by Eq. (9):

$$q_{bj} = \sum_{i=1}^{T_j} q_{ib} = \sum_{i=1}^{T_j} (\varphi_P \xi_{tbi} \xi_{sbi} q) \tag{9}$$

where q_{ib} is the heat consumption rate of gas turbine with evaporative cooling intake system in the i-th hour; ξ_{tbi} and ξ_{sbi} are correction factors of the outlet temperature and moisture content to the heat consumption of the gas turbine with evaporative cooling system in the i-th hour, which are obtained by Fig. 5 and Fig. 6 respectively.

The average output per hour and average heat consumption per hour can be calculated by using the relationship of $\overline{P_2} = P_2/8760$ and $\overline{Q_2} = Q_2/8760$ respectively.

Since the temperature and relative humidity taken are the average temperature and relative humidity of each month, the corresponding correction factors for each month are also fixed, and the power generation and heat consumption rate per hour in the same month are considered to be the same, then P_{aj}, q_{aj}, P_{bj} and q_{bj} can be expressed by the following formulas:

$$P_{\mathrm{aj}}=\sum_{i=1}^{T_j} P_{ia}=T_j P_{\mathrm{ia}}; \qquad q_{aj}=\sum_{i=1}^{T_j}(P_{ia}q_{ia})=T_j P_{ia}q_{ia} \tag{10}$$

$$P_{\mathrm{bj}}=\sum_{i=1}^{T_j} P_{ib}=T_{\mathrm{j}} P_{\mathrm{ib}}; \qquad q_{bj}=\sum_{i=1}^{T_j} P_{ib}q_{ib}=T_j P_{ib}q_{ib} \tag{11}$$

5. Calculation and verification

Under the standard operating condition (Atmospheric temperature = 15°C, relative humidity = 60%, atmospheric pressure = 1.013bar), for PG6111FA gas turbine, P = 75.87 MW, q = 10300 kJ/(kW·h) [22].

In the paper, monthly mean temperature and relative humidity in Baltic Sea coast were chosen as meteorological parameters of gas turbine without evaporative cooling system [23], which were shown in Fig. 8. The reader can read wet bulb temperature, moisture content at inlet dry bulb temperature and wet bulb temperature from psychrometric chart for calculation [24]. Meteorological parameters of gas turbine with evaporative cooling system can be calculated by Eq. (2) and Eq. (3).

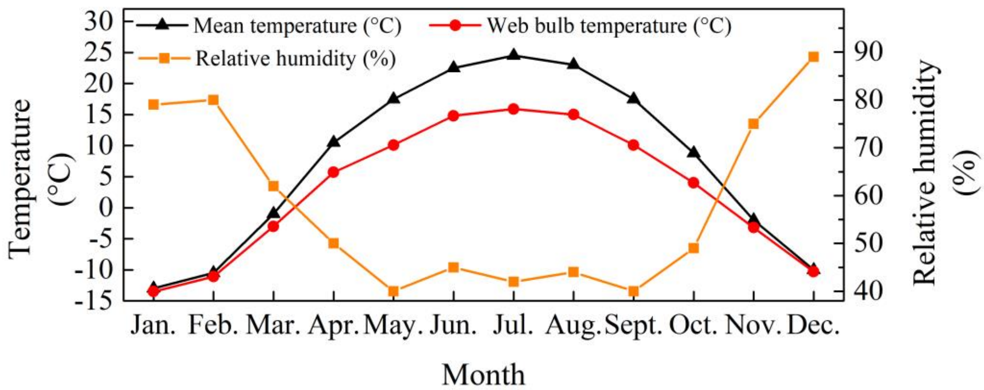

Fig. 8. Meteorological parameters of gas turbine without evaporative cooling system

When the inlet temperature reaches 5°C, the evaporative cooling intake system needs to run, that is the system can be used for 5136 hours in the whole year. During the running of system, the resistance will increase by 250 Pa. Therefore, according to the influence of intake pressure loss on the output and heat consumption rate, it can be obtained when the intake resistance increases 250 Pa, $\varphi_p = 99.96\%$ and $\varphi_q = 100.0125\%$.

Then, for gas turbine with and without evaporative cooling intake system, the corresponding performance parameters can be calculated by taking corresponding coefficient into the corresponding formula.

6. Results and discussion

Based on the data calculated, Fig. 9 and Fig. 10 are drawn respectively as following:

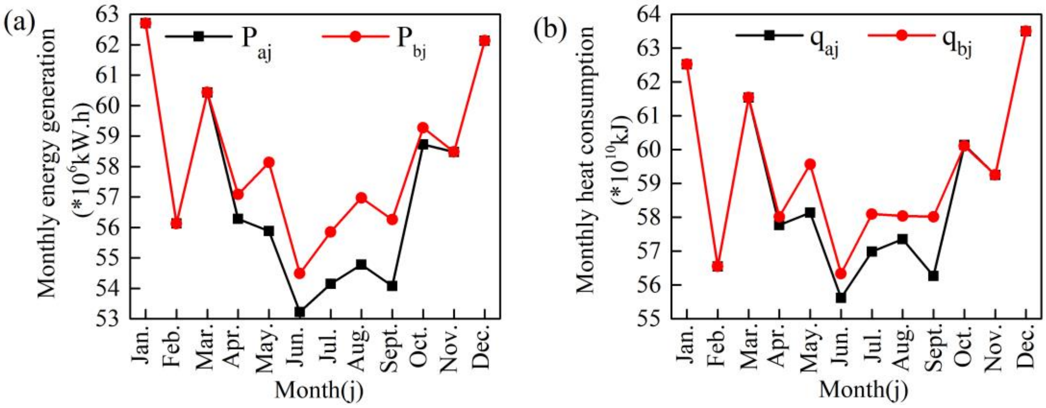

Fig. 9. Monthly energy generation (a) and monthly heat consumption (b) before and after installation of intake evaporative cooling system

As can be seen from Fig. 9a, during each month of the operation of the evaporative cooling intake system, the energy generation has been improved, among which, the monthly increment of energy generation in October is the lowest at 552776.36 kW·h, which is 0.95% of the energy generated during the month when the evaporative cooling intake system is not in operation. While the monthly power generation increased most in May, from 55882807.22 kW·h to 58134877.36 kW·h, with an increase rate of 4.03%. Therefore, it is very beneficial to install an evaporative cooling intake system for gas turbine in terms of monthly power generation.

Also, it can be seen from Fig. 9b that the use of evaporative cooling intake system has increased the heat consumption of each month by a certain amount, with the largest increase rate of 2.5% in May, but in October, the heat consumption has basically remained unchanged. Considering the change of monthly power generation, it is obvious that the higher the monthly power generation increment caused by evaporative cooling intake system, the higher the heat consumption increase, but the increase of monthly power generation is higher than that of heat consumption increase.

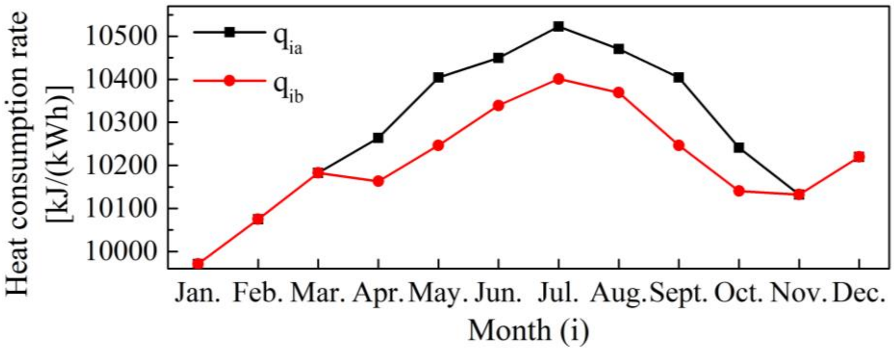

Fig. 10. Monthly heat consumption rate before and after installation of intake evaporative cooling system

Moreover, from the curves shown in Fig. 10, it can be found that the monthly heat consumption rate of the system is reduced by 0.97% ~ 1.51%. While heat consumption rate is the ratio of heat consumption to the output of the gas turbine, the decrease of heat consumption rate shows that the effect of evaporative cooling intake system on the output of gas turbine is higher than that on heat consumption. Therefore, it can be concluded that the operation of the evaporative cooling intake system in Baltic Sea voyage has brought obvious economic benefits during the year of adding the evaporative cooling intake system to gas turbine by considering Fig. 9 and Fig. 10.

Furthermore, the results of comparative analysis before and after installing the intake evaporative cooling system are recorded in Table 1:

Table 1

Comparison of performance parameters

Cooling Scheme	Annual average output [MW]	Annual average heat consumption rate [kJ/(kW•h)]	Average output increment [MW]	Annual energy generation [MW•h]	Energy gain [MW•h]
Before installation	78.43	10292	-	687010	-
After installation	79.56	10146	1.13	696957	9947

From the table above, it can be found that in the year of using the intake evaporative cooling system in Baltic Sea voyage, the annual energy generation increased by 9947 MW·h, the annual average output increased by 1.13 MW. At the same time, the monthly heat consumption is increased by a certain amount, but the heat consumption rate is reduced to 10146 kJ/(kW·h) from 10292 kJ/(kW·h) in the view of the whole year (8760 h). So the net increase in electricity generation within a year of using the intake evaporative cooling system is considerable.

7. Conclusions

Based on the analysis of the influencing factors of the gas turbine performance parameters and the calculation of the performance parameters, the following conclusions are obtained: (1) The operation performance of the gas turbine is related to the loss of the intake resistance, the intake air temperature and the moisture content of the intake air. Especially, the lower the intake air temperature, the higher the operation efficiency of the gas turbine. (2) In Baltic Sea voyage, the system can be used for 5136 h in the whole year, accounting for 59% of the whole year time. (3) The use of evaporative cooling intake system can significantly increase the power generation and reduce the heat consumption rate. Investment in the evaporative cooling intake system is no doubt an effective measure to increase the power generation to obtain a good return.

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