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Thermodynamics evaluation of gas turbine cycle of Zahedan gas power plant with simultaneous use of absorption inlet air cooling and steam injection

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Abstract

The temperature of the exhaust gases from simple gas turbines is high, and therefore, gas turbines have low thermal efficiency. Also, high ambient air temperature reduces the output power and thermal efficiency of the cycle. This paper examines a system that uses a heat recovery boiler to recycle exhaust gases and produce steam. Steam is produced in a double-pressure boiler. Low-pressure steam is introduced into the lithium bromide single-acting absorption chiller to cool the air entering the compressor, and high-pressure steam is injected into the combustion chamber of the gas turbine. The main purpose of this paper is to study and analyse (energy, exergy and environmental) gas turbine system with steam injection with cooling of the inlet air. The gas turbine cycle of the Zahedan gas power plant was modelled based on Heat Recovery Steam Injection (HRSG). Then energy and exergy are carried out. Also, the effect of steam injection and inlet air cooling on heat efficiency, output power, fuel consumption, exergy efficiency and total system price was studied and presented. The results showed that with a 10% spray of steam inside the combustion chamber, the output power increased by 11.03% and the thermal efficiency of the cycle increased from 24.4% to 26%.

Keywords: Absorbtion Inlet air cooling, Exergy and Energy analysis, Gas turbine, Heat Recovery Steam Injection
2020 MSC: 37N05, 80Axx

1 Introduction

The simple thermodynamic processes of a gas turbine cycle are modelled as the Brighton cycle. This cycle has very low efficiency, especially during peak hours in the summer. Bouam [4] analysed the improvement of the main characteristics of gas turbines at high ambient temperature conditions with steam spraying in the combustion chamber and examined the effect of ambient temperature, pressure ratio, spraying parameters and combustion chamber temperature in the cycle with and without steam spraying. Huang [7] analysed the gas turbine cycle with steam injection exergy and evaluated the efficiency of the second law to evaluate the thermal performance of the system. Moliere [9] empirically summarised the main trends and evolution of gas turbine technology in terms of improving efficiency and reducing NOx pollutants. In the Srinivas study [12], a thermodynamic evaluation was performed for a combined cycle with steam injection in a gas turbine with a two-pressure heat recovery generator.

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The operation of a gas turbine is highly dependent on ambient temperature. As the air temperature increases, the density and consequently the mass flow rate of the passing air decrease. Reducing the mass flow rate results in a lower turbine output power. The energy required by the chiller is supplied by the exhaust gases from the gas turbine. Nasser and Elkalay [10] investigated a simple absorption chiller system of heat-recycled lithium bromide to cool the compressor inlet air in Bahrain. They calculated that by reducing the ambient temperature from 40 to 10° C, a 10% increase in power is obtained. Bies [11] studied the application of a dual-effect absorption chiller of lithium bromide to cool the hot air entering the gas turbine compressor. Ameri and Hejazi [1] performed an economic analysis of the cooling air system of the inlet to the gas turbine in Chabahar power plant in Iran.

In this study, the whole system was first modelled and analysed. The heat recovery boiler was modelled as two pressures. High-pressure steam is injected into the combustion chamber, and low-pressure steam is used to start the absorption chiller. The total cost includes investment costs, operating costs (total fuel and maintenance costs, and fines for NOx emissions. Changes in power output, thermal efficiency, and exergy efficiency increase with increasing percentage of vapour injection into the combustion chamber, as well as the amount of Inlet air cooling, were investigated, and the results were presented.

2 Energy and Exergy Analysis

2.1 Energy Analysis

The schematic of the gas turbine with steam injection in the combustion chamber with cooling of the inlet air by the absorption chiller is shown in Figure 1.

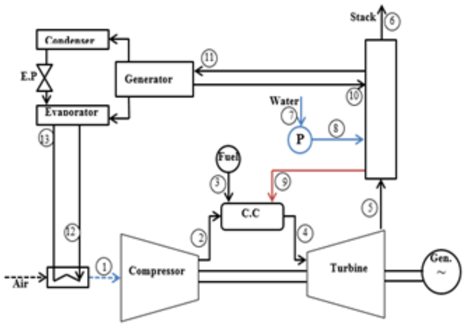

Figure 1: Whole shemetic diagram of STIG-HRSG-AIC

An energy analysis of the gas turbine was carried out based on the Brayton cycle principles and included energy balance at the system inlet and outlet. The laws of continuity and energy balance equations in the Compressor are as follows:

$$\dot{m}_2 = \dot{m}_1 + \dot{m}_{10}, \qquad \dot{W}_{\text{comp.}} = \dot{m}_2 \times C_{P,\text{air}} \times (T_2 - T_1), \qquad T_2 = T_1 \left[1 + \frac{1}{\eta_{\text{comp.}}}\left(\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right)\right]. \tag{2.1}$$

The laws of continuity and energy balance equations in the combustion chamber are as follows:

$$\dot{m}_4 = \dot{m}_2 + \dot{m}_3 + \dot{m}_9, \qquad \dot{m}_2 h_2 + \dot{m}_3 \eta_{\text{CC}} LHV + \dot{m}_9 h_9 = \dot{m}_4 h_4. \tag{2.2}$$

The laws of continuity and energy balance equations in the turbine are as follows:

$$\dot{m}_4 = \dot{m}_5, \qquad \dot{W}_{\text{turb.}} = \dot{m}_g C_{P,\text{gas}}(T_4 - T_5), \qquad T_5 = T_4 \left[1 - \eta_{\text{turb.}}\left(1 - \left(\frac{P_5}{P_4}\right)^{\frac{k-1}{k}}\right)\right]. \tag{2.3}$$

Using the first law of thermodynamics, the output power of the turbine is obtained from the following equation:

$$\dot{W}_{\text{net}} = \dot{W}_{\text{turb.}} - \dot{W}_{\text{comp.}} - \dot{W}_{\text{pump}}. \tag{2.4}$$

Therefore, the thermal efficiency of the gas turbine cycle are calculated as follows:

$$\eta_{\text{overall}} = \frac{\dot{W}_{\text{net}}}{\dot{m}_f \times LHV}. \tag{2.5}$$

As shown in Figure 2, the single-pressure heat recovery steam generator consists of three components: the economizer, evaporator and super heater to produce superheated steam at high pressure.

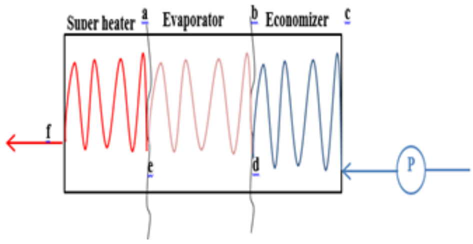

Figure 2: Shemetic diagram of HRSG

The laws of continuity and energy balance equations in the HRSG are as follows:

$$\dot{m}_8 = \dot{m}_9, \quad \dot{m}_5 = \dot{m}_6 \tag{2.6}$$

$$\dot{m}_5(h_5 - h_a) = \dot{m}_8(h_d - h_8) \tag{2.7}$$

$$\dot{m}_5(h_a - h_b) = \dot{m}_8(h_e - h_d) \tag{2.8}$$

$$\dot{m}_5(h_b - h_c) = \dot{m}_8(h_f - h_e) \tag{2.9}$$

Some water from the drum is drained out to control the concentration of solid particles inside the drum, and it's negligible. The inlet air cooling system should be designed to avoid air freezing at the compressor inlet. Therefore, the minimum inlet air temperature cooled by the absorption chiller of lithium bromide and water is considered to be 12° C. The cooling load consists of two parts. Part of this cooling is related to lowering the ambient air temperature until its relative humidity is 100% and the other part is to reduce the air temperature to below the dew point. Figure 3 shows the cooling process in a psychrometric diagram.

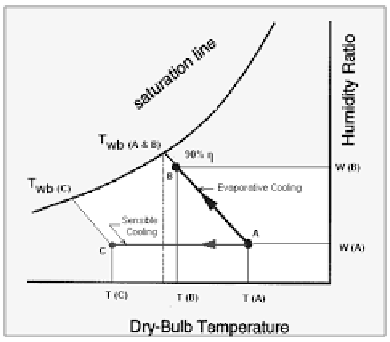

Figure 3: Air cooling process in psychometric diagram [11]

Therefore, the total cooling load of the chiller that it should produce is calculated as follows:

$$\dot{Q}_{\text{Air}} = \dot{m}_A(q_s + q_l), \quad q_s = h_d - h_c, \quad q_l = h_{fg}(\omega_a - \omega_d), \tag{2.10}$$

where q_s and q_l are tangible heat and latent heat, respectively. In order to analyze the cycle and obtain the thermodynamic properties of lithium bromide solution and water such as temperature, pressure, concentration, enthalpy and entropy, the relationships prepared by ASHRAE [5] and reference [8] have been used.

Heat transfer values are calculated by writing mass and energy conservation laws for the evaporator, condenser, generator, and absorber chiller [6].

$$\dot{Q}_{\text{eva}} = \dot{m}_r(h_{11c} - h_{l0c}), \qquad \dot{Q}_{\text{cond}} = \dot{m}_r(h_{7c} - h_{8c}), \qquad \dot{Q}_{\text{des}} = \dot{m}_c h_{4c} + \dot{m}_r h_{7c} - \dot{m}_{3c} h_{3c} \tag{2.11}$$

$$\dot{m}_{\text{Sg}} = \frac{\dot{Q}_{\text{des}}}{(h_{17c} - h_{18c})}, \qquad \dot{Q}_{\text{abs}} = \dot{m}_r h_{12c} + \dot{m}_{6c} h_{6c} - \dot{m}_{1c} h_{1c}. \tag{2.12}$$

We also have soluble (SHX) and refrigerant (RHX) heat exchangers [6]:

$$\dot{m}_{2c}h_{2c} + \dot{m}_{4c}h_{4c} = \dot{m}_{3c}h_{3c} + \dot{m}_{5c}h_{5c} \tag{2.13}$$

$$\dot{m}_{8c}h_{8c} + \dot{m}_{11c}h_{11c} = \dot{m}_{9c}h_{9c} + \dot{m}_{12c}h_{12c} \tag{2.14}$$

Pump consumption as well as COP chiller performance coefficient are calculated as follows:

$$\dot{W}_p = \frac{\dot{m}_1 c\,(h_{2c} - h_{1c})}{\eta_p}, \qquad COP = \frac{\dot{Q}_{\mathrm{eva}}}{\dot{Q}_{\mathrm{des}} + \dot{W}_p} \tag{2.15}$$

2.2 Exergy Analysis

Exergy is defined as the maximum work that can be done to bring the system into equilibrium with its surroundings. In fact, exergy represents the quality of energy. Exergy analysis is a combination of the first and second laws of thermodynamics. The exergy rate equilibrium equation for the steady state control volume is calculated as follows [2]:

$$0 = \sum_J \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \dot{W}_{\mathrm{CV}} + \dot{E}_{\mathrm{in}} - \dot{E}_{\mathrm{out}} - \dot{E}_{\mathrm{D}}. \tag{2.16}$$

Exergy efficiency is defined as follows:

$$\psi_{\mathrm{tot}} = \frac{\dot{E}_{\mathrm{out}}}{\dot{E}_{\mathrm{in}}} = 1 - \frac{\dot{E}_{\mathrm{D,\,tot}} + \sum \dot{E}_{\mathrm{Loss}}}{\dot{E}_1 + \dot{E}_5 + \dot{E}_{11} + \dot{E}_f + \dot{E}_{13c}} \tag{2.17}$$

where E_{Loss} is the exergy drop, which includes the exergy of the exhaust gases from the recycling boiler.

3 Simulation results

We consider a simple gas turbine with a net output power of 16.77 MW in ISO conditions. The effect of inlet air cooling on the net output power and thermal efficiency of this gas turbine in different spray ratios is shown in Figures 4 and 5. As can be seen, by decreasing the inlet air temperature to the compressor and also increasing the steam injection ratio in the combustion chamber, the output power and cycle efficiency increase.

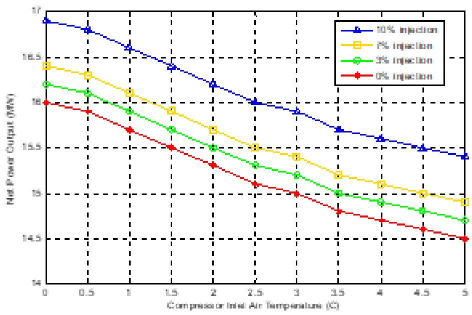

Figure 4: Effect of inlet air cooling on output power at different spray ratios without combustion chamber

Inlet air cooling increment with steam injection by 10% decreases the mass rate of the air passing through, 16.9 MW power and 25.9% efficiency to 15.4 MW and 24.5% MW, respectively. Figures 6 and 7 show the effects of steam injection inside the combustion chamber on the output power and thermal efficiency of the cycle at ambient temperature (32° C). It is understood that with 10% steam sprays, the output power increases by 11.03% and the cycle efficiency changes from 24.4% to 26%.

The exergy efficiency of the whole system and how it changes with the amount of steam injection and cooling of the inlet air are shown in Figure 8. According to this figure, with increasing the amount of steam spraying into the combustion chamber and increasing the cooling of the inlet air, the exergy efficiency of the whole system increases.

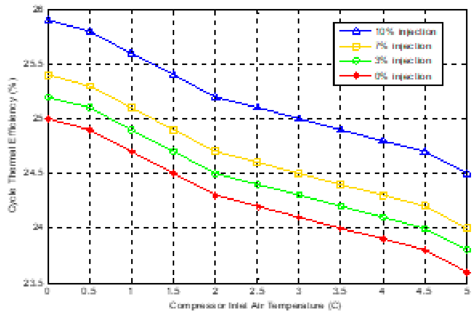

Figure 5: The effect of inlet air cooling on the thermal efficiency of the cycle in different spray ratios without combustion chamber

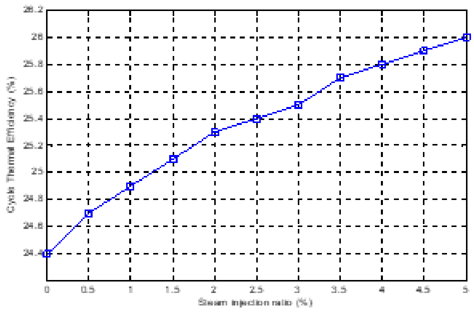

Figure 6: The effect of non-combustion chamber steam injection amount on cycle thermal efficiency

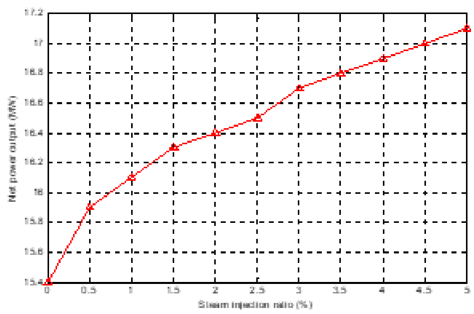

Figure 7: The effect of non-combustion chamber steam injection amount on output power

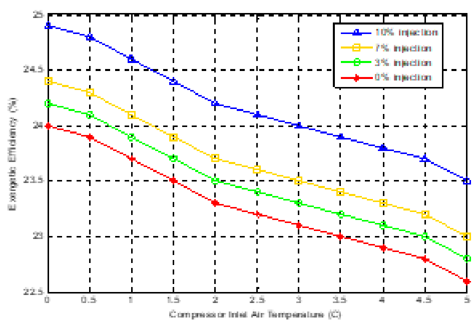

Figure 8: Changing the amount of steam spraying and air cooling

4 Conclusion

In this paper, the gas turbine system was modelled by steam injection and cooling of the inlet air by an absorption chiller and analysed from different energy and exergy aspects. In order to consider the environmental aspect of the system and control the amount of NOx produced, a cost was considered as a penalty for NOx production and its relationships were presented.

The results showed that with 10% spray of steam inside the combustion chamber, the output power increased by 11.03% and the thermal efficiency of the cycle increased from 24.4% to 26%. However, in the case of simultaneous use of 10% steam injection and cooling of the air entering the compressor, the output power of the gas turbine system increased by 5.625% and the thermal efficiency of the cycle increased from 3.6% in the case without spray and cooling. By increasing the amount of steam sprayed into the combustion chamber and increasing the cooling of the inlet air, the exergy efficiency of the whole system increases.

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