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Thermodynamic analysis of gas turbine with air bottoming cycle

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ABSTRACT

In this study, thermodynamic analysis of a gas turbine cycle with air bottoming cycle is presented to compare the efficiency ratios with modified gas turbine cycle as well as with conventional combined cycle. Both the modified gas turbine and modified gas turbine with air bottoming cycles consist of an intercooler and reheat exchangers. First and second laws of thermodynamics are employed in the analysis of each cycle. Codes are written in MATLAB to solve the equations at different operating conditions and efficiencies are calculated. The effects of pressure ratio of the topping gas turbine cycle ($3 \le pr_{g_1} \le 15$) and the pressure ratio of the bottoming gas turbine cycle ($3 \le pr_{g_2} \le 12$) on the thermal efficiency ratio and the work output are explored. It is observed that the basic gas turbine cycle with air bottoming cycle has a 4.78% higher efficiency than the basic gas turbine at their maximum efficiencies. Comparisons of thermal efficiency ratio and work output are presented for various combinations of each cycle. It is found that modified gas turbine with air bottoming cycle produces 1.27-fold higher work output than the modified gas turbine cycle at their maximum efficiencies. But it has less thermal efficiency and less work output than the combined cycle at all operating conditions. The exergy analysis shows that the use of the gas turbine bottoming cycle reduces the total exergy destruction of simple gas turbine by 6%. The exergy loss with the exhaust gas of simple gas turbine constitutes a large portion of 47% of the total exergy destruction. This is reduced to 31% for gas turbine with air bottoming cycle.

1. Introduction

In conventional power plants, gas turbine is the major source of power generation in many countries. The gas turbine works on the principle of Brayton cycle in which compressed air from the compressor enters the combustion chamber. The high pressure and high temperature combustion products from the combustion chamber enter the gas turbine where they expand to low pressure and produce the work [1]. Due to incomplete combustion in the combustion chamber as well as short expansion of high pressure and high temperature combustion products in the gas turbine, a lot of energy gets lost to the environment which not only pollutes the environment but also plays the vital role in global warming. Sometimes this lost energy is abundant that is capable to run another thermal power plant. The turbine exhaust temperature of a simple gas turbine is in the range of 370–540 °C but usually above 500 °C [2]. Accordingly, the hot exhaust gases have significant thermodynamic utility (exergy) that would otherwise be lost when the exhaust gas discarded directly to the surroundings.

One way of utilizing this potential is by means of internal heat recovery in which exhaust gas is utilized as the source of heat. The various methods being employed include a regenerative heat exchanger and steam injection. The regenerative heat exchanger allows the air exiting the compressor to be preheated before entering the combustor, thereby reducing the amount of fuel that must be burned in the combustor. With the steam injection method, the thermal energy of the exhaust gas is transferred to an auxiliary fluid (water) in HRSG (heat recovery steam generator) unit which is then injected into the combustor. In the HRSG unit, water passes in a counter flow with the exhaust gas into three separate heat exchangers: economizer, vaporizer and superheater. Steam injection increases the turbine work by increasing the mass flow rate of the working fluid and its specific heat [3]. In addition to an increase in turbine output, steam injection method has the advantage of controlling NO_x emissions from the gas turbine combustor [4].

The combined cycle arrangement is another way to utilize the hot exhaust gas. The energy source for the bottoming cycle such as a steam cycle is the hot exhaust gas from the topping cycle. The

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Nomenclature

E_D	exergy destruction, kW
E_L	exergy losses, kW
h	enthalpy, kJ/kg
IC	intercooling
p	pressure, Pa
pr	pressure ratio
Q	heat input, kW
RG	regenerative
RH	reheat
s	entropy, J/K
T	temperature, °C
v	specific volume, m^3/kg
$\dot{V}$	volume flow rate, m^3/s
W	power output, kW
$\dot{m}$	mass flow rate, kg/s
η	efficiency
ψ	specific flow exergy, kW/kg

Subscripts

0	reference
1	inlet of the compressor or pump
2	outlet of the ideal compressor or pump
3	inlet of the turbine
4	outlet of the ideal turbine
c	compressor
cc	combine cycle
D	destruction
g_1	topping gas turbine
g_2	bottoming air turbine cycle
g_3	lower bottoming air turbine cycle
i	intermediate condition in multi-stages compression or expansion
L	loss
s	steam cycle
r	ratio
T	total
t	turbine

thermal efficiency of the combined cycle is greater than either cycle because the gas turbine has higher average temperature for heat addition and the vapor cycle has lower average temperature for heat rejection. Some recent gas-steam combined-cycle work plants have achieved efficiencies above 60% [5]. They are used worldwide for electric power generation. Many researchers proposed different techniques to recover energy from the gas turbine hot exhaust gasses in order to improve the performance of the cycle. The researchers investigated the effect of process parameters on the performance of the gas turbine equipped with the internal heat recovery components and/or the combined cycle. Those parameters include the pressure ratio, turbine inlet temperature, pressure drop in the combustion chamber, and the temperature at the inlet of the compressor. Carapellucci [6] studied the improvement of the gas turbine by steam injection and regenerative heat exchanger methods in two configurations. In the first configuration, the exhaust gas exiting the turbine passes through the HRSG unit and the generated steam is injected into the combustor. In the second configuration, the exhaust gas first goes to a regenerative heat exchanger to preheat the air exiting the compressor and then goes into the HRSG unit. The study concluded that the second configuration has an efficiency that is close to that of the conventional combined cycle at turbine inlet temperature of 1200 °C or less, with the additional advantageous of design simplicity over the combined cycle. Najjar [7] reviewed some methods of improving combined-cycle performance through the use of heat recovery process such as enhancing the power output by increasing the mass flow rate through the addition of saturated air was suggested by Higdon et al. [8]. This method is different from steam injection in that it uses an air saturation unit to evaporate heated water below its boiling point. The calculated efficiency of the system is found to be 54.8% as compared to 47.9% for an inter-cooled steam-injected system. Polyzakis et al. [9] studied four configurations: SC (simple cycle), IC (intercooled cycle), RH (reheated cycle) and IC/RH (intercooled and reheated cycle). Their results showed that the most desirable element with the combined cycle work plant is the reheater. Darwish et al. [10] investigated the feasibility of utilizing the hot exhaust gases leaving the gas turbine to superheat the steam leaving the steam generator as well as heating the feed water returning to the steam generator of the nuclear power plant condenser. The result shows that this gives an increase in thermal efficiency up to 50%. This is a significant increase, compared to 33% in the case of conventional NPP (nuclear power plant) and 36% in the case of GT (gas turbine), even at ISO (International Organization for Standardization) condition. The work output of the conventional NPP steam cycle is increased by 90% (from 607 MW to 1151.4 MW) without burning any extra fuel, while the GT work output remains almost unchanged. Meanwhile, the combined-cycle work output increases from the work output of the two separate plants of 1580 MW [$=607+(4\times 243)$] to the combined-cycle work output of 2124 MW [$=1151.1+(4\times 243)$]. This output is more than 34% above the output of the two separate plants. The study of Xiang and Chen [11] of a combined gas turbine cycle shows that increasing the HRSG inlet temperature has less influence on steam cycle efficiency when it is over 590 °C. The study also shows that the combined plant efficiency of gas-to-gas heat recuperator can rise up to 59.05% at base load.

Ibrahim and Rahman [12] studied the effects of the operating conditions on the performance of the CCGT (combined cycle gas turbine). Their simulation results show that the overall efficiency and the total work output increase with the increase of the compression ratio and the turbine inlet temperature and the decrease of the ambient temperature. The peak overall efficiency was reached with a higher compression ratio and low ambient temperature. The overall efficiencies for CCGT are found to be 59% compared to 54% for the GT plants. Ibrahim et al. [13] studied the thermodynamic analysis of combined cycle gas turbine performance with different configurations for gas turbine: simple gas turbine, two shaft gas turbine, intercooler gas turbine and regenerative gas turbine. Their simulation results show that combined cycle with regenerative gas turbine configuration has higher overall efficiency, but produces less total work output compared with other configurations. A comparative study of the performance of the SBCC (supercharged boiler combined cycle) with the conventional combined cycle based on energy was performed by Abdel-Moneim and Hossin [14]. Their results indicate that the output work of the SBCC is 1.6–2.1 fold higher than that of conventional combined cycle when operating at same conditions but the SBCC efficiency was found to be lower than the conventional combined cycle because in SBCC boiler an increase in the work output is offset by the external heat supplied.

Several studies showed that performance of a gas turbine depends on the inlet air temperature of compressor. Ashley et al. [15] reported that for every degree (K) rise in ambient temperature