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Utilization of exhaust gases heat from gas turbine with air bottoming combined cycle

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ABSTRACT

This study investigates the utilization of heat from the exhaust gas and the exhaust air of gas turbine with air bottoming combined cycle (GT-AB) by using steam and absorption bottoming cycles in different combinations. For the utilization of heat from both sources, the results indicate that the maximal efficiency occurs at a GT pressure ratio of 11, the AB pressure ratio is 6 for utilization of heat of the GT exhaust gas and 3 for the utilization of heat of AB exhaust air. The results indicate that for maximal efficiency, utilization of heat from the GT exhaust gas and the AB exhaust air is best performed by the absorption system in a cogeneration plant. However, when the cooling effect of the absorption cycle is used to lower the compressor inlet temperature of the GT and AB cycles, it was found that utilization of heat from the GT exhaust gas by the absorption cycle and utilization of heat from the AB exhaust air by the steam cycle produces the maximal power output.

1. Introduction

The exhaust gases of a simple gas turbine usually discarded to the surroundings at temperature above 500 °C with a significant losses of exergy [1]. Regenerative heat exchangers and steam injection are common means of internal heat recovery (cf. [2], [3]). A regenerative process preheated the air exiting the compressor before entering the combustor. In steam injection method, the steam that is generated in a heat recovery steam generator (HRSG) unit using the thermal energy of the exhaust gas heat to water which then is injected into the combustor. The regenerative process reduces the amount of fuel that must be burned in the combustor for the same power output and steam injection increases the mass flow rate of the working fluid and thus the turbine work [4]. Passing the gas turbine exhaust gas through a regenerative heat exchanger to preheat the air exiting the compressor and then into the HRSG unit to generate steam for steam injection, at TIT of 1200 °C or less, increases the efficiency of the gas turbine to value that is close to that of the conventional combined cycle, with the additional advantageous of system simplicity [5].

A steam bottoming cycle (ST) is an external heat recovery system for using the heat of the exhaust gas from the topping gas turbine cycle. Together they form the combined cycle (GT-ST). The thermal efficiency of the GT-ST cycle is proven to be greater than of either individual cycle because the gas turbine has higher average temperature for heat addition and the vapor cycle has lower average temperature for heat rejection. The effects of process parameters on the performance of the combined cycle are investigated in several studies. Those parameters include the pressure ratio, turbine inlet temperature, pressure drop in the combustion chamber, and the temperature at the inlet of the compressor. [6], [7] investigated the effect of these parameters on the GT-ST combined cycle. Their simulation results for an isentropic compressor efficiency of 85% show that the thermal efficiency of the combined cycle increases from 52 to 57% when the pressure ratio is increased from 6 to 24, while the total work output decreases linearly from 2.6 to 1.9 kW. At the GT pressure ratio of 18, raising the turbine inlet temperature from 1150 to 1450 K raises the thermal efficiency from 55 to 58%; at constant turbine inlet temperature, raising the compressor inlet temperature from 273 to 337 K raises the thermal efficiency of the combined cycle by about 2%. Techniques such as reheat and intercooling used in simple turbine cycles are also used in the GT-ST for improving the performance of the cycle. [8] studied four configurations: simple GT-ST, GT-ST with intercooler, GT-ST with reheat and GT-ST with intercooler and reheat. Their results showed that GT-ST with reheat has higher thermal efficiency of 53.8% at the optimum pressure ratios of 14 and 3 of first- and

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Nomenclature

E	Rate of exergy, W
h	enthalpy, kJ/kg
MR	the ratio of the mass flow rate of the strong solution to the mass flow rate of the refrigerant
$\dot{m}$	mass flow rate, kg/s
p	pressure Pa
T	temperature, *K*
v	specific volume, m^3/kg
W	work per unit mass of mass flow, J/kg
x_s	strong solution concentration by mass %
x_w	weak solution concentration by mass %
η_{cc}	thermal efficiency
η_{cp}	power efficiency
ψ	rate of exergy destruction

Subscripts

a	ambient
c	compressor
p	pump
r	ratio
s	steam
t	turbine
1	inlet of the compressor or pump
2s	outlet of the ideal compressor or pump
2	actual state at the exit of the compressor or pump
2″	intermediate condition in multi-stages compression
3	inlet of the turbine
4s	outlet of the ideal turbine
4	actual state at the exit of the turbine

Abbreviation

AB	air bottoming cycle
AC	absorption cycle
GT	gas turbine cycle
GT-AB	gas turbine with air bottoming cycle
GT-ST	gas turbine with steam bottoming cycle
HRSG	heat recovery steam generator
PP	pinch point, °C
ST	steam cycle
TIT	turbine inlet temperature, °C
VMC	vapor compression cycle

second-expansion stages respectively. Exhaust gas of gas turbine cycle is also used to improve the low efficiency of the nuclear steam power plants (NPP). [9] studied the performance of a cogeneration plant of water-cooled nuclear reactor with fossil-fuel superheating, where the nuclear reactor generated steam at an evaporation temperature of 234 °C and a fossil-fuel combustor superheated that steam to 400 - 600 °C, in addition to providing heat to the feed-water heater. The results show that this can increase the plant efficiency by at least 16% relative to that of the nuclear reactor plant without that fossil fuel superheat. [10] studied the performance of incorporating a gas turbine power cycle into the nuclear steam power plant (GT-NPP). The hot exhaust gases from gas turbine units are utilized for superheating the steam leaving the nuclear steam generator before it is supplied to the steam turbine, and to heat the feed water coming from the condenser and before entering the nuclear steam power plants steam generator. Their results show that the power output of the Nuclear steam power plants can increases from 600 MW to 1151.4 MW when exhaust gas is utilized and the thermal efficiency of the GT-NPP combined cycle increases from 33% for NPP alone to 49%. [11] shows that the installation of CO_2 transcritical Rankine cycle at the outlet of the stack of a combined-cycle power plant (Iran) to recover the heat of a flue gases at 150 °C, can recover 4040 kW which constitutes 0.9% of the plant capacity and increases the plant thermal efficiency by nearly 0.4%.

Power plants are usually designed as co-generation plants to produce both electric power and process heat. In some current installations, this process heat is used to drive MSF desalination plants. [12] suggests that, in case reverse osmosis is chosen to replace MSF in the future, cogeneration plants can use their waste heat to operate absorption cooling systems instead, which should easy to do because they are driven by steam or hot water in a temperature range similar to the conditions used by the MSF desalting units. [13] studied a cogeneration system comprising an absorption chiller used for air-conditioning and a GT-ST combined cycle. The study investigated different parameters, and found that the overall efficiency is strongly influenced by the steam to gas mass ratio. When this ratio is 0.12, the combined cycle efficiency is maximal. Other parameters such as steam turbine inlet temperature of the steam cycle and ambient temperature are very weakly affected the efficiency of the combined cycle.

Studies showed the dependence of a gas turbine performance on the compressor inlet air temperature. [14] reported that for every degree (K) rise in ambient temperature above ISO condition, the gas turbine loses 0.1% of thermal efficiency and 1.47 MW of its Gross Work Output. Najjar [15] studied cooling the air at the inlet of the GT cycle using an aqua-ammonia absorption refrigeration system bottoming gas turbine engine. The results show that at TIT of 1400 K, gas turbine pressure ratio of 12 and temperature at the inlet of the absorption generator of 225 °C, improves power output by about 21%, the thermal efficiency by about 38%, and the overall specific fuel consumption by 28%. [16] studied lowering the intake air temperature of a combined cycle to 15 °C using an absorption system powered by part of the steam generated in heat recovery steam generator at a low-pressure steam of about 0.6–0.8 MPa. The results show that this method increases the power output of the GT by 10.6% but decreases the power output of the steam cycle by 2.43%. The net effect is an increase in the power output of the combined cycle by 6.24%. In similar study, [17] studied using part of the steam generated in the HRSG to power lithium bromide absorption chillers that provide gas turbine compressor turbine inlet air-cooling and another portion of the steam is utilized to meet part furnace heating. The study shows that the gas turbine and steam combine cycle provides power output of 15.6 MW, and the absorption chillers provides 45 MW of cooling capacity assuming the coefficient of performance of 1.3, in addition to 2.7 MW of process heating. Several studies ([18]- [24]) compare different methods of turbine intake inlet cooling on the performance of gas turbine cycle. [18] compares cooling the turbine intake air of a single gas turbine cycle by water-lithium bromide absorption chiller powered by the gas turbine exhaust gas waste-heat to that using evaporative coolers and mechanical vapor-compression chillers. Their study shows that at the same ambient conditions, absorption cooling system increases the work output by 23.2% as opposed to 4.2%, for evaporative coolers and mechanical vapor-compression chillers would require an additional 2.7 MW of electric energy to provide