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Two new high-performance cycles for gas turbine with air bottoming

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ABSTRACT

The objective of this research is to model steam injection in the gas turbine with Air Bottoming Cycle (ABC). Based on an exergy analysis, a computer program has been developed to investigate improving the performance of an ABC cycle by calculating the irreversibility in the corresponding devices of the system. In this study, we suggest two new cycles where an air bottoming cycle along with the steam injection are used. These cycles are: the Evaporating Gas turbine with Air Bottoming Cycle (EGT-ABC), and Steam Injection Gas turbine with Air Bottoming Cycle (STIG-ABC). The results of the model show that in these cycles, more energy recovery and higher air inlet mass flow rate translate into an increase of the efficiency and output turbine work. The EGT-ABC was found to have a lower irreversibility and higher output work when compared to the STIG-ABC. This is due to the fact that more heat recovery in the regenerator in the EGT-ABC cycle results in a lower exhaust temperature. The extensive modeling performed in this study reveals that, at the same up-cycle pressure ratio and turbine inlet temperature (TIT), a higher overall efficiency can be achieved for the EGT-ABC cycle.

1. Introduction

The gas turbine, first introduced in 1937 by Brown Boveri of Switzerland [1], is a major player in the huge power generation market nowadays. The early gas turbines had a thermal efficiency of only 17% [1]. In recent years, the performance of gas turbines has been improved due to the need for a higher fuel to electricity conversion efficiency [2]. It has been shown that the thermal efficiency of a gas turbine can be increased by raising the pressure ratio and the turbine inlet temperature (TIT), and by using the turbine exhaust energy in a thermal recuperation process in a bottoming cycle [3,4]. In a recent study in 2010, Datta et al. [5] provided both energy and exergy analyses of an externally fired gas turbine (EFGT) cycle with an integrated biomass gasifier. They also investigated the effects of operating parameters like the pressure ratio and TIT. They showed that the specific air flow, associated with the size of the plant equipment, decreased with the increase of the pressure ratio. They also found that an increase in the TIT reduced the specific air flow.

One common solution for increasing the performance of a gas turbine is to couple the Brayton cycle with the Rankine cycle. In this method, the hot exhaust gases available at the end of the expansion stage in the topping cycle, are used to produce hot high-pressure steam in the bottoming cycle [6]. This method, however, may not be feasible in a small scale power plant because of extra capital investments needed for a high-pressure steam generator, a steam turbine, a condenser, and special water treatment facilities [7].

Combining the gas turbine cycle with an air bottoming cycle (ABC) is another method that has been introduced to increase the performance of a gas turbine [4]. Fig. 1 shows such a combined cycle in which the exhaust of an existing, topping gas turbine is sent to a gas-air heat exchanger that heats the air in the secondary gas turbine cycle. The ABC was first patented by Farrell of General Electric company in 1988 [8] who explains many industrial advantages of an air bottoming cycle. In the same year, Alderson [9] also introduced an air bottoming cycle for the use in a coal gasification plant. In 1995, Kambanis [10] showed that by using the exhaust gas of a simple gas turbine (General Electric LM2500) in the air bottoming cycle, the off-design efficiency of the combined cycle improved from 36% to 47% at a maximum 21,625 kW. Also in 1996, Bolland [11] found that the combined LM2500PE gas turbine and ABC shaft efficiency increased to about 46.6%. In a review paper, Poullikkas [2] reported that the output power was increased by 18–30% in the ABC cycle compared to that of the simple gas turbine. The efficiency was also increased up to 10 percent. In 1998, Korobitsyn [4] compared the performance of an ABC cycle with that of a steam bottoming cycle (SBC) where he concluded that the ABC can have a performance values close to and exceeding those of the SBC. Also, Korobitsyn in 2002 [7] concluded that the combination of a gas turbine and an ABC represents a high efficiency Combined Heat and Power (CHP) plant that provides clean, hot air at a temperature of 200–270 °C for process needs.

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Nomenclature

ABC	air bottoming cycle
b	specific Darrieus function (kJ/kg), $b = h + ke + pe - T_0 s$
CC	combustion chamber
EGT-ABC	evaporative gas turbine with air bottoming cycle
EGT	evaporating gas turbine cycle
h	specific enthalpy (kJ)
HAT	humid air turbine cycle
HAWIT	humid air water injected turbine cycle
HRSG	heat recovery steam generator
I	irreversibility (kJ)
$\dot{m}$	mass flow rate (kg/s)
Q_{LHV}	lower heating value (MJ/kg)
P	pump; Pressure (kPa)
R	specific-gas constant (kJ/kgK)
R_c	pressure ratio in upping cycle
r_c	pressure ratio in bottoming cycle
s	specific entropy k (kJ/kgK)
STIG-ABC	steam injection gas turbine with air bottoming cycle
STIG	steam injection gas turbine cycle
t	time (s)
T_0	ambient temperature (°C)
TIT	turbine inlet temperature (°C)
W	work interaction (kJ)
y	mole fraction in the vapor phase

Greek letters

η	efficiency
Φ	extensive closed-system exergy (kJ)
$\Phi_{Q,i}$	exergy transfer associated with Q_i at T_i
ψ_{tot}	sum of thermomechanical and chemical stream exergy (kJ)

Subscripts

CV	control volume
o	exit state value
i	inlet state value
0	thermomechanical (restricted) dead state
00	environmental (unrestricted) dead state
comb	combustor
comp	compressor
f	fuel
turb	turbine
2s	isentropic state of compressor discharge
4s	isentropic state of the turbine outlet

The efficiency of an ABC cycle can be further increased by inter-cooling the air in the compressor stages as has been proposed by Najjar et al. [12] in 1996. In their parametric study, they found that for a compression ratio of 10 in the topping cycle and 2 in the bottoming cycle, and a TIT of 1400 K, the thermal efficiency can be increased to about 49%.

The steam injection can also be used to improve the efficiency and specific work in gas turbine with ABC as suggested in this study. Steam injection has been used for power augmentation in industrial gas turbines since 1960s [2]. In 1978, Cheng (cited by [2]) proposed a gas turbine cycle in which the exhaust heat was used to produce steam in a heat recovery steam generator; this steam was injected in the combustion chamber of the gas turbine, resulting in a gain in the efficiency and an increase in the output power. The cycle is commonly called the Cheng cycle or the steam injection cycle [2]. Since then, the gas turbine wet cycles (cycles with steam injection) were developed in various types with the aim of efficiency and emissions improvement. The simpler types of wet cycles are Steam Injection Gas turbine (STIG) [13–15] and Evaporative Gas Turbine (EGT) [16]. In the STIG cycle, the steam raised in a Heat Recovery Steam Generator (HRSG) downstream of the turbine, is injected into the combustion chamber or into the turbine inlet. But in the EGT, water is injected into the compressor discharge where it is evaporated; the mixture may then be further heated in the 'cold' side of a heat exchanger in what is essentially a generative gas turbine cycle [16,17]. Also in 2002, Traverso and Massardo [18] proposed two new cycles named Humid Air Turbine cycle (HAT) and Humid Air Water Injected Turbine cycle (HAWIT) with the aim of improving the efficiency of the gas turbine cycle and lowering the irreversibilities. The two introduced cycles present good performance at high-pressure ratios [18].

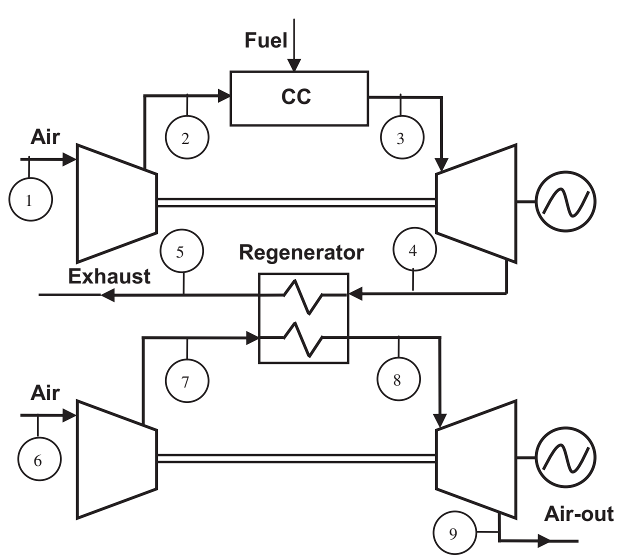

Fig. 1. Gas turbine with air bottoming cycle.

In this study, we suggest two other cycles where an air bottoming cycle along with the steam injection are used. Fig. 2 shows Steam Injection Gas Turbine with Air Bottoming Cycle (STIG-ABC); the topping exhaust gases have high temperature after passing through the regenerator. Thermal energy of these gases can be used for evaporating water. The steam is then mixed with ABC compressor discharged air in a mixer. The evaporating process is done in the HRSG. Fig. 3 also shows a schematic of the Evaporative Gas Turbine with Air Bottoming Cycle (EGT-ABC). Water is injected into a container (called evaporator) where the hot discharged air of compressor and the injected water are in contact; this makes a mixture of air and vapor with a lower temperature that increases the mass flow rate of the compressor discharge. Increasing the temperature difference across the regenerator causes a better energy recovery. More energy recovery and higher air inlet mass flow rate translate into an increase of the efficiency and output turbine work in the STIG-ABC and EGT-ABC. In this work both STIG-ABC and EGT-ABC systems are investigated using a developed computer program and the results of the two cases are compared to each other. In these two cycles with steam injection, we do not encounter the disadvantage of sulphur compound that makes corrosion that happens in normal steam injection gas turbine cycles. The performance of the two introduced cycles in this