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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 intercooling 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].

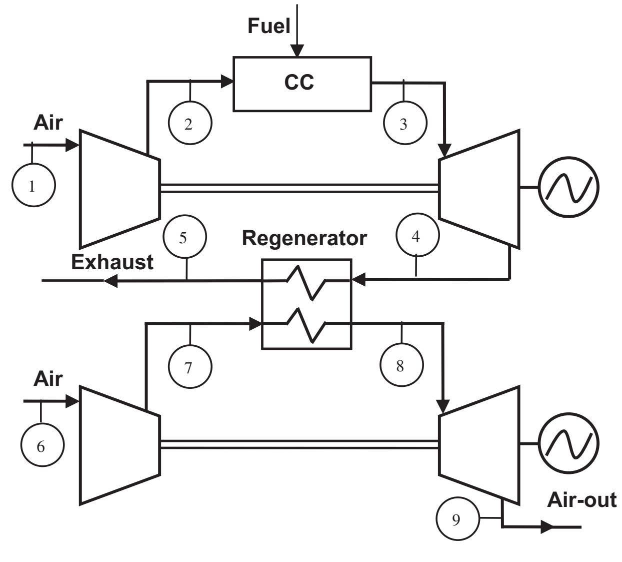


Fig. 1. Gas turbine with air bottoming cycle.

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

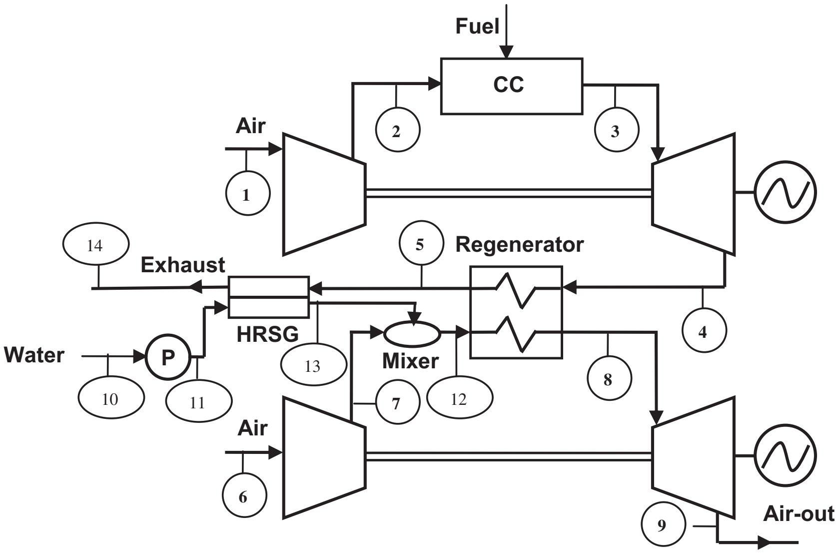


Fig. 2. A schematic of the steam injection gas turbine with air bottoming cycle (STIG-ABC).

study is also compared with that of the HAT and HAWIT cycles proposed by Traverso and Massardo [18].

2. Computer model

The main assumptions used in the computer model are as follows. The combustion products and the inlet air that make up the working fluids in the gas turbine with ABC are treated as ideal gases. Other thermodynamic assumptions used in the present analysis are reported in Table 1 [1,3,4,10,16].

2.1. Calculations

The computer model developed in this study includes the calculation of four cycles: simple gas turbine, ABC, STIG-ABC, and EGT-ABC. For a simple gas turbine cycle, the calculation procedure is as follows. The pressure drop due to air filtering before the compressor is considered. The inlet air enters the compressor at state 1. Considering an isentropic efficiency of η_{comp} for the compressor and a pressure ratio ofR_{c}, the state 2 at the compressor outlet can be calculated as:

$$R_{\mathrm{c}} = \frac{P_2}{P_1} \tag{1}$$

$$\left(\dot{S}_{T_{2s}} - \dot{S}_{T_1}\right) - \dot{m}RLn\frac{P_2}{P_1} = 0 \tag{2}$$

$$\eta_{\mathrm{comp}} = \frac{h_{2S} - h_1}{h_2 - h_1} \tag{3}$$

The calculation was performed with different TITs. For a specified TIT, the exhaust temperature and the specific work of the cycle can be obtained as follows. Having considered the combustion chamber pressure drop, combustion chamber efficiency, mechanical compressor efficiency, mechanical turbine efficiency and mass flow rate of the fuel, we can have:

$$H_3 - H_2 = \eta_{\mathrm{comb}}\dot{m}_f Q_{\mathrm{LHV}} \tag{4}$$

$$\left(\dot{S}_{T_{4s}} - \dot{S}_{T_3}\right) - RLn\frac{P_4}{P_3} = 0 \tag{5}$$

$$\eta_{\mathrm{turb}} = \frac{h_3 - h_4}{h_3 - h_{4S}} \tag{6}$$

$$w_{\mathrm{cycle}} = h_1 + h_3 - h_2 - h_4 \tag{7}$$

Table 1
Thermodynamic assumptions.

Air filter pressure drop	1.5%
Isentropic compressor efficiency	88%
Combustion chamber pressure drop	2%
Combustion efficiency	98%
Isentropic turbine efficiency	90%
Turbine mechanical efficiency	99%
Compressor mechanical efficiency	99%
Regenerator effectiveness	85%
Regenerator pressure drop (hot fluid)	2%
Regenerator pressure drop (cold fluid)	2%
Intercooler thermal Effectiveness	75%
Intercooler pressure drop	2%
HRSG efficiency	75%
HRSG pressure drop (water and steam)	6%
HRSG pressure drop (flue gases)	2%
Mixer pressure drop	0.5%
Evaporator pressure drop	0.5%
Pump efficiency Hydraulic	80%

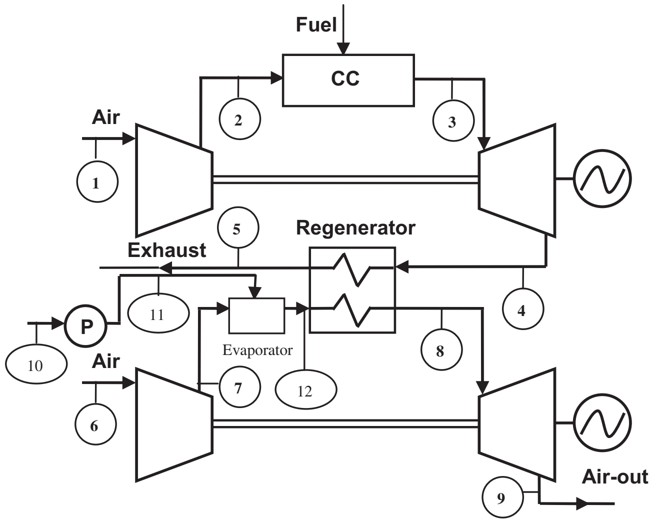


Fig. 3. A schematic of the evaporative gas turbine with air bottoming cycle (EGT-ABC).

Similarly, the calculation model for a gas turbine with air bottoming cycle (Fig. 1) can be developed; the procedure is given in Flowchart 1 in the Appendix. Fig. 2 shows the STIG-ABC system; the differences between the ABC gas turbine and STIG-ABC are the HRSG and a mixer which provides steam for the bottoming cycle. The state of the up-cycle exhaust (state 14 in Fig. 2) was considered the saturated condition ($\phi_{14} = 100\%$). Flowchart 2 shows the STIG-ABC calculation procedure.

Fig. 3 shows the EGT-ABC system, the differences between the ABC gas turbine and EGT-ABC are the evaporator and a pump which provides water for the bottoming cycle. The exhaust state of the up-cycle (state 5 in Fig. 3) was considered the saturated condition ($\phi_5 = 100\%$). The calculation procedure for this cycle is presented in Flowchart 3 in the Appendix.

For all cycles, the irreversibility is calculated in the model from the exergy balance for a steady-state control volume as [19]:

$$\frac{d\Phi_{cv}}{dt} = \sum \dot{\Phi}_{Q,i} + \sum \dot{m}_i b_i - \sum \dot{m}_o b_o + \dot{W}_{act} - \dot{I}_{cv} \tag{8}$$

where $d\Phi_{cv}/dt$ is the non flow exergy of the control volume, $\sum \dot{\Phi}_{Qi}$ the exergy transfer associated with heat transfer, $\sum \dot{m}b$ stream exergy, $\dot{W}_{\text{act}}$ the actual work transfer, and $\dot{I}_{cv}$ the irreversibility. The exhaust exergy of each cycle is calculated per mole of the exhaust as follows [19]:

$$\psi_{\text{tot}} = \sum_{i=1}^{n} y_i \left[h_{i,T} - h_{i,T_0} - T_0\left(s^0_{i,T} - s^0_{i,T_0}\right)\right] + RT_0 \ln\frac{P}{P_0} + RT_0 \sum_{i=1}^{n} y_i \left(\ln\frac{y_i}{y_{i,00}}\right) \tag{9}$$

where ψ_{tot} is the total exhaust exergy of an ideal gas mixture per mole of the exhaust, y_i the mole fraction of each species, $h_{i,T}$ the enthalpy of each species at the exhaust temperature, $h_{i,T0}$ the enthalpy of each species at the environmental state. T_0 and P_0 are the ambient temperature and pressure, respectively. $s^0_{i,T}$ and $s^0 i, T_0$ are the standard entropy of each species at the exhaust and environmental temperatures, respectively. R is the specific-gas constant and $y_{i,00}$ is the mole fraction of each species at the standard atmospheric conditions.

In this work, MATLAB 7.3 software was employed to perform the calculations. Each device of a power plant cycle is defined as a function in MATLAB; these functions are used to calculate the parameters related to that device. Tables of thermodynamic properties [19] available for air, combustion products and steam are used in the program.

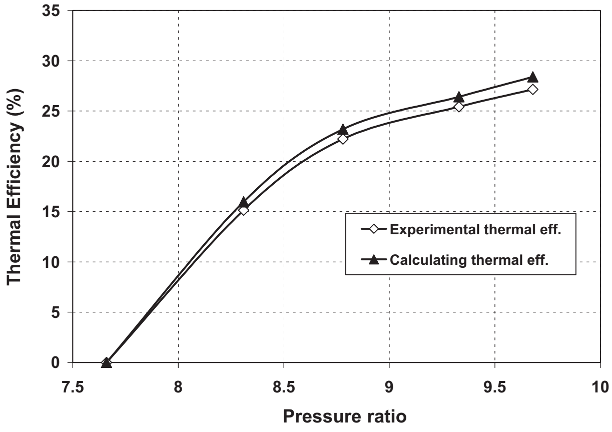


Fig. 4. Comparison of model results with those of the experiments [20] for the GE-F5 simple gas turbine.

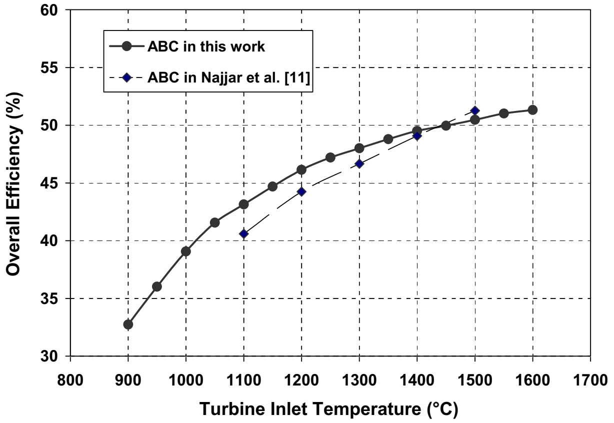


Fig. 5. Comparison of model results with those of Najjar et al. [12] for the GE-F5 simple gas turbine.

2.2. Model validations

To validate the model, the results of the program are compared to those of the experiments performed by Ghazikhani et al. [20] for the GE-F5 simple gas turbine, and also to the results obtained by Najjar et al. [12] for the ABC cycle. Fig. 4 shows a comparison of model results with those of the experiments [20] for the thermal efficiency against pressure ratio, where a good agreement is observed. As pressure ratio is increased the thermal efficiency is also increased. The discrepancy between the two results is less than 5%. Fig. 5 shows the comparison between the results of the model with those of Najjar et al. [12] for the overall efficiency in an ABC cycle. As TIT is increased the efficiency is also increased. In this case, the difference between the two results is less than 7% which indicates a good agreement.

3. Results and discussion

Table 2 shows a comparison between the results of the model for the overall efficiency in different cycles. The TIT was considered 1400 °C and that of the ambient 25 °C for all systems. The pressure ratio of the simple gas turbine and that of the topping cycle of other systems was 25. For the bottoming cycles, the pressure ratio was considered to be 6. The percentage of the specific work increase compared to that of the simple gas turbine cycle is also given in the table.

As seen in the table, the STIG-ABC and EGT-ABC cycles generate more specific work and are more efficient than that of the gas turbine with ABC. This result can be attributed to a better topping cycle heat recovery in the STIG-ABC and EGT-ABC due to the steam injection in these two cycles. Fig. 6 compares the steam-to-air ratio on the mass basis for these cycles against the TIT. As seen in the figure, the steam-to-air ratio is increased with the TIT for both cycles. The ratio, however, is larger for the EGT-ABC cycle. This is due to the higher temperature of saturated air at the state of 8 ($\phi_8 = 1$) for the EGT-ABC cycle (Fig. 3) when compared with that of saturated air at the state of 12($\phi_{12} = 1$)for the STIG-ABC cycle (Fig. 2).

Table 2
The overall efficiency and the percentage increase of specific work for different systems (TIT = 1400 °C, T_0 = 25 °C, R_c = 25 and r_c = 6).

Cycle Type	Overall efficiency (%)	Specific work increase (%)
Simple GT	41.53	0
ABC	49.83	20.1
STIG-ABC	52.43	26.8
EGT-ABC	54.63	31.8

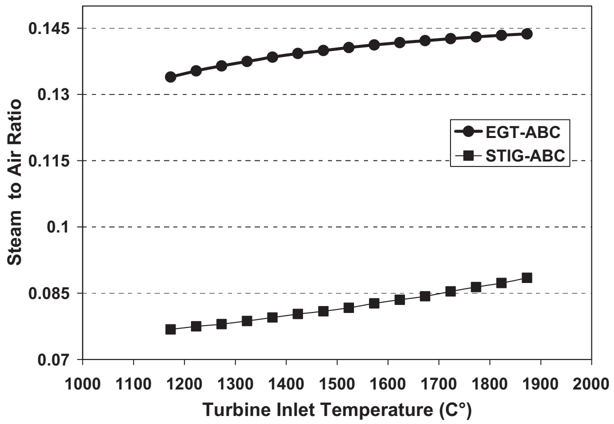


Fig. 6. Steam-to-air ratio on the mass basis against TIT for the STIG-ABC and EGT-ABC cycles (TIT = 1400 °C, $T_0 = 25$ °C, $R_c = 25$ and $r_c = 6$).

To have a clear comparison between the four cycles, an exergy analysis is performed. Fig. 7 shows an exergy balance for each cycle. The output work of the simple gas turbine is lower than that of the other ABC cycles due to the absence of the exhaust heat recovery in a simple gas turbine. For the STIG-ABC, the output work is higher than that of the ABC due to the additional exhaust heat recovery in the HRSG system in the STIG-ABC cycle. The EGT-ABC cycle has the highest output work because of the more possibility of water injection (Fig. 6) and the absence of the HRSG irreversibility (Figs. 2 and 3). Fig. 7 also shows that for the EGT-ABC cycle, the exhaust exergy is the lowest. This can be explained by that fact that more heat recovery in the regenerator in the EGT-ABC cycle results in a lower exhaust temperature.

Fig. 8 displays the variation of the overall efficiency of the four cycles against the net work output at a wide range of up-cycle pressure ratio of 8–40 (with an interval of 2). As observed in the figure, the EGT-ABC cycle has a better performance. This is again due to the better energy recovery and lower irreversibility associated with the EGT-ABC cycle. The figure shows that increasing the up-cycle pressure ratio increases the cycle efficiency. For a simple gas turbine, compared to other cycles, the efficiency is more sensitive to the pressure ratio. As observed for the ABC's cycles, a high efficiency of more than 50% (much higher than that of a simple gas turbine) is achieved with a small pressure ratio of 25. This phenomenon can be explained by the fact that in the simple gas turbine, there is only a single cycle. In the ABCs cycles, however, the efficiency not only is affected by the up-cycle but also by the energy recovery in the bottom-cycle. In the gas turbine industry, the pressure ratio is optimized based on two important parameters namely the cycle efficiency and specific work. The optimized condition is selected such that while the efficiency is increased the specific work is not notably decreased. As Fig. 8

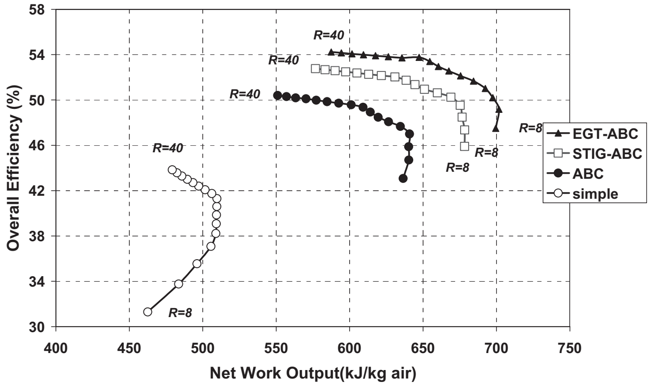
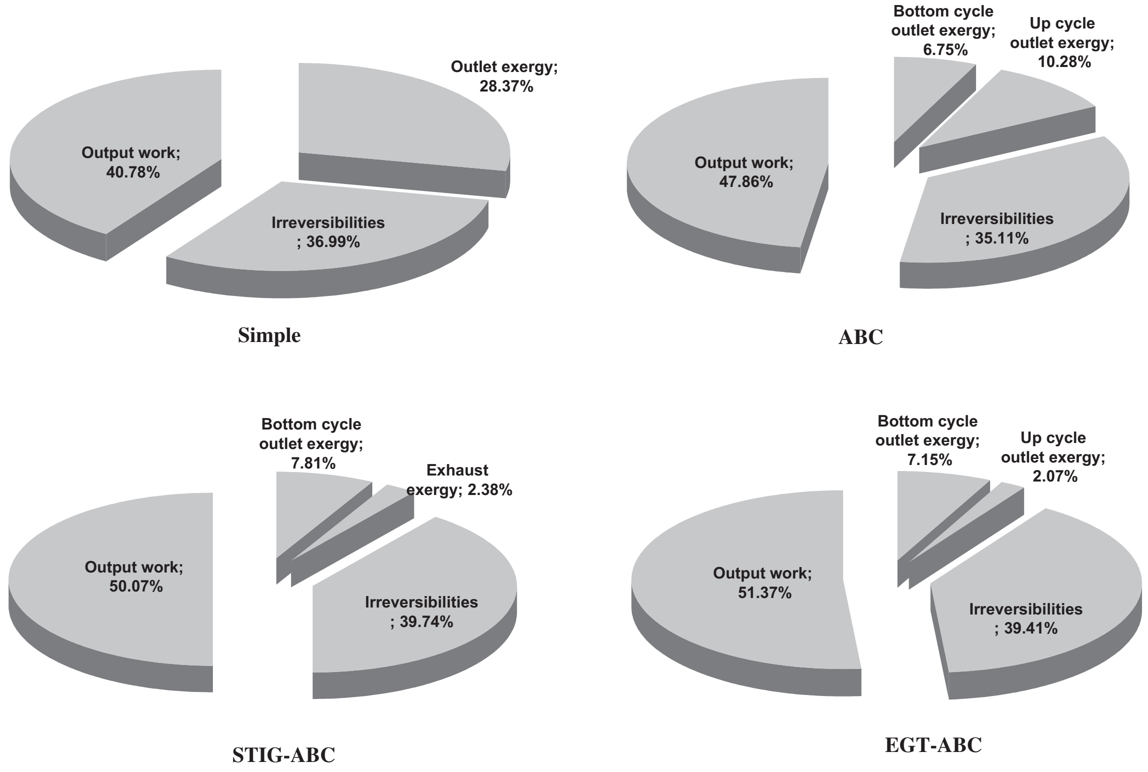


Fig. 8. Overall efficiency variation against net work output at various up-cycle pressure ratios (TIT = 1400 °C, $T_0 = 25$ °C and $r_c = 6$).



Simple

ABC

STIG-ABC

EGT-ABC

Fig. 7. Model results for the exergy balance in the four considered cycles (TIT = 1400 °C, $T_0 = 25$ °C, $R_c = 25$ and $r_c = 6$. For the simple cycle there is no bottoming cycle).

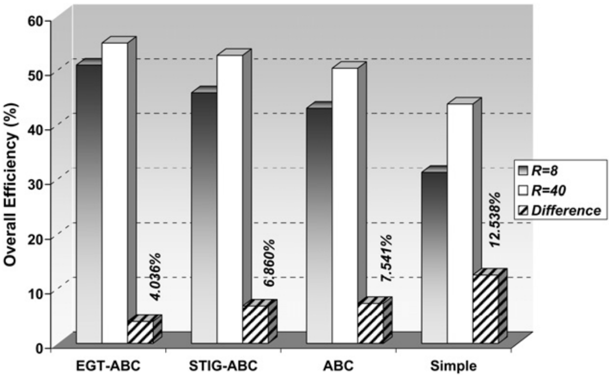


Fig. 9. Increase of the overall efficiency due to up-cycle pressure ratio in a range of 8–40 ($T_0 = 25$ °C, TIT = 1400 °C and $r_c = 6$).

shows, the overall efficiency for pressure ratios above 20 in all the ABC's cycles is not affected as much as for the simple cycle. For instance in the EGT-ABC cycle, the optimum pressure ratio is 25 for which the cycle efficiency is around 54% and the specific work is 650 kJ/kg of air (Fig. 8); this is an industrial advantage of the EGT-ABC cycle that the optimum condition can be achieved at a lower up-cycle pressure ratio. The above point is more clearly shown in Fig. 9 where the increase of the overall efficiency with pressure ratio in the range of 8–40 is displayed for all cycles.

The variation of the overall efficiency against ambient temperature is presented in Fig. 10. For all cycles, the efficiency reduces as the ambient temperature is increased. As seen in Fig. 10, although the overall efficiency of the ABC's is higher than that of the simple cycle, the rate of efficiency reduction with ambient temperature in the simple cycle is lower. This is because in the ABC's the overall efficiency is affected by two factors. At a constant TIT, the efficiency of the up-cycle is reduced by increasing the ambient temperature. At the same time, the effectiveness of the heat recovery in the bottom-cycle is also decreased due to a smaller difference between the two stream temperatures. Fig. 10 also shows the advantage of the EGT-ABC cycle for having the highest efficiency in different ambient temperatures. The above argument is best seen in Fig. 11 where the lost of the efficiency and specific work by increasing ambient temperature for different cycles are displayed. The percentage of the efficiency and work lost is minimal for the EGT-ABC cycle due to a higher opportunity of energy recovery. Increasing the ambient temperature leads to a higher temperature of the compressor discharged and, as a result, more water can be evaporated which, in turn, translates into more mass flow rate passing through the turbine resulting in an increase of the turbine work.

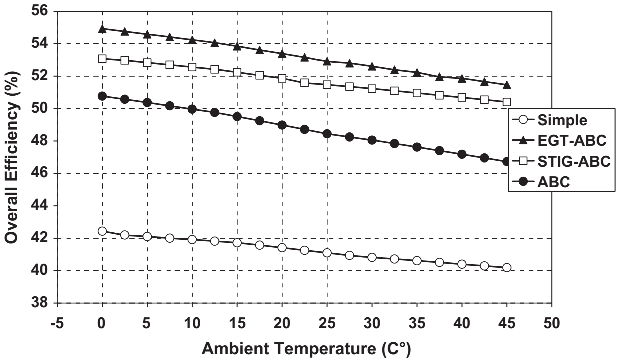


Fig. 10. Efficiency variation against ambient temperature (TIT = 1400 °C, $R_c = 25$ and $r_c = 6$).

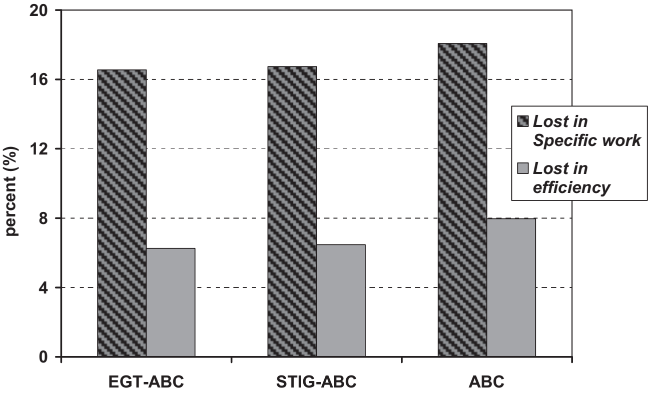


Fig. 11. The lost efficiency and lost work due to an ambient temperature change from 0 to 45 °C (TIT = 1400 °C, $R_c = 25$ and $r_c = 6$).

One of the important advantages of the EGT-ABC in comparison with other cycles is a lower TIT at the same overall efficiency. Fig. 12 shows such a comparison between different cycles. For example for an overall efficiency of 50%, the TIT is around 1450 °C, 1250 °C, and 1150 °C for the ABC, the STIG-ABC, and the EGT-ABC, respectively. The figure also shows that the maximum achievable overall efficiency of a simple gas turbine at 1600 °C is nearly 42%; however, for the same efficiency, the EGT-ABC works at a considerably lower TIT of only 950 °C. As seen in Fig. 12, the overall efficiency of the EGT-ABC is higher than that of the STIG-ABC at the same TIT. A detailed quantitative comparison between the EGT-ABC and STIG-ABC is given in Table 3 where the values of overall efficiency and specific work corresponding to a wide range of variations related to the operating conditions are presented. As seen from the table, for all operating conditions, the EGT-ABC cycle has a better performance. The EGT-ABC is also preferred to the STIG-ABC because of some other reasons. The EGT-ABC does not need additional equipments (HRSG seen in Figs. 2 and 3) and it has a lower sensitivity to pressure ratio as seen in Fig. 8. Therefore, the remaining of the results and discussion presented in this paper is focused on the EGT-ABC in more details.

Fig. 13 shows the efficiency variation against net work output for different up-cycle pressure ratios (with an interval of 3.83) at various TITs in the EGT-ABC. As seen in the figure, the EGT-ABC is suitable for the TITs higher than 1200 °C; at lower values of TITs, however, the overall efficiency is reduced as the pressure ratio is increased. This is because the recovered exergy in the bottoming cycle for the TITs lower than 1200 °C cannot compensate the work required for the up-cycle compressor working at a high-pressure ratio. The figure also reveals that the optimum net work output with a high overall efficiency can be achieved at pressure ratios within 20–30 for the

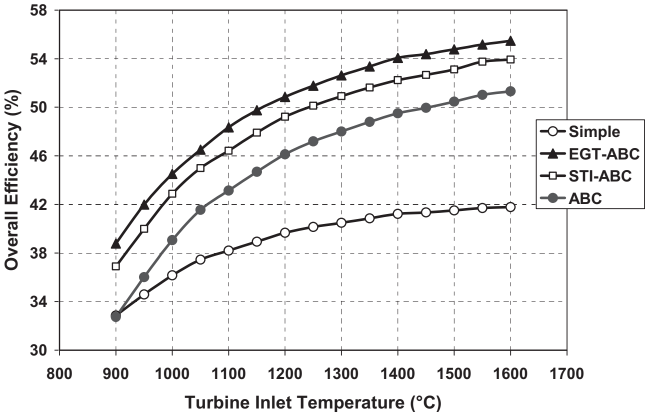


Fig. 12. The efficiency variation against TIT ($R_c = 25$, $r_c = 6$ and $T_0 = 25$ °C).

Table 3
Variation of overall efficiency and specific work for different values of TIT, $T_0$and $R_c$associated with the EGT-ABC and STIG-ABC cycles. For all cases, the bottoming-cycle pressure ratio is $r_c = 6$.

TIT (°C)	T_0 (°C)	R_c	EGT-ABC		STIG-ABC	
			Overall Efficiency (%)	Specific Work (kJ/kg air)	Overall Efficiency (%)	Specific Work (kJ/kg air)
900	5	8	43.39	333.99	38.99	300.20
		20	42.97	251.25	38.44	224.84
		32	38.79	183.27	34.21	161.66
	20	8	41.49	304.77	37.33	274.24
		20	39.78	215.87	35.36	191.95
		32	33.10	140.26	28.71	121.70
	35	8	40.34	283.37	35.96	252.73
		20	36.45	183.43	32.32	162.70
		32	27.11	102.94	23.03	87.48
1200	5	8	47.66	568.86	43.81	523.01
		20	51.71	518.63	47.93	480.80
		32	52.37	464.62	48.28	428.42
	20	8	46.56	538.65	42.95	497.03
		20	50.27	482.24	46.62	447.28
		32	50.29	420.75	46.34	387.82
	35	8	45.68	513.23	42.32	475.56
		20	48.93	449.25	45.46	417.51
		32	48.36	382.47	44.63	353.04
1400	5	8	48.83	733.70	45.14	678.32
		20	53.97	705.69	50.43	659.53
		32	55.45	659.38	51.91	617.46
	20	8	48.02	703.39	44.53	652.39
		20	53.00	669.20	49.54	625.59
		32	54.23	616.75	50.67	576.35
	35	8	47.33	676.93	44.09	630.74
		20	52.06	635.36	48.77	595.34
		32	53.03	578.11	49.63	541.18

TITs higher than 1200 °C. The above points regarding the EGT-ABC cycle can also be observed in Fig. 14 where the overall efficiency vs. the up-cycle pressure ratio at different TITs is displayed.

Having obtained the results for the EGT-ABC, the performance of this cycle can now be compared with that of the HAT and HAWIT cycles proposed by Traverso and Massardo [18]. They reported that for a specific work of higher than 600 kJ/kg, the best performance of the HAT and HAWIT cycles at a TIT of 1400 °C corresponds to a pressure ratio of about 30 where the efficiency is higher than 48% (Fig. 7 of reference [18]). Figs. 13 and 14 show that for the same conditions (i.e. the specific work of higher than 600 kJ/kg and a TIT of 1400 °C) in the EGT-ABC, an overall efficiency of 55% can be achieved at an up-cycle pressure ratio of about 24.

Fig. 15 displays the variation of the overall efficiency against the pressure ratio of the bottoming cycle in different TITs. Comparing Figs. 14 and 15, it can be seen that the effect of the pressure ratio of the bottoming cycle on the overall efficiency is nearly similar to that of the up-cycle. At the TITs lower than 1200 °C, the exhaust temperature is decreased and, therefore, there is less opportunity for the energy recovery in the regenerator; under this condition, increasing the pressure ratio of the bottoming cycle only results in an increase of the compressor work. The optimum operating conditions for a gas turbine cycle can be determined based on the values of the TIT and the pressure ratio. For the EGT-ABC cycle, introduced in this paper, the optimum conditions can be inferred based on Figs. 14 and 15 as: a TIT of around 1200 °C, an up-cycle pressure ratio of nearly 25, and a bottoming-cycle pressure ratio of approximately 6. Under these conditions, an overall efficiency of nearly 47% can be achieved.

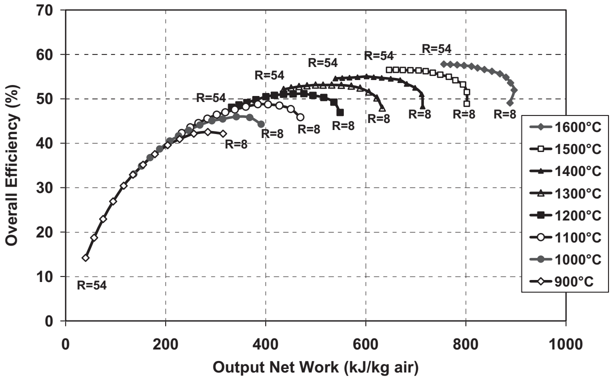


Fig. 13. The overall efficiency variation against net work output for the EGT-ABC at an up-cycle pressure ratio of 8–54 in various TITs ($r_c = 6$ and $T_0 = 25$ °C).

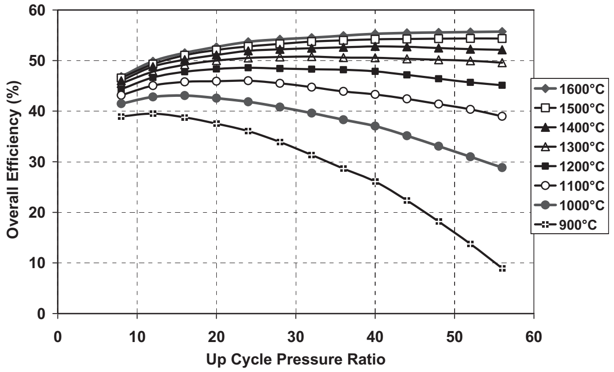


Fig. 14. The overall efficiency variation against up-cycle pressure ratio for the EGT-ABC in various TITs ($r_c = 6$ and $T_0 = 25$ °C).

4. Sensitivity analysis

A sensitivity analysis, similar to what has been proposed by Badami and Mura [21], is conducted in order to better understand the effect of key-parameters in the performance of the cycles. In this analysis, the effect of an additional percentage of individual parameters TIT, T_0, $R_c$andr_c on the overall efficiency and specific work are investigated using MATLAB 7.3 software. The base conditions related to this sensitivity analysis are: TIT = 1400 °C, ambient temperature $T_0 = 25$ °C, topping cycle pressure ratio $R_c = 25$ and bottoming-cycle pressure ratio $r_c = 6$. For these specific conditions, Tables 4 and 5 show the details of the sensitivity analysis. As seen from the tables, the system performance for all cycles has a low sensitivity related to both the topping- and bottoming-cycle pressure ratios. More sensitivity is observed for all cycles associated to the ambient temperature. All cycles, however, are most sensitive to the turbine inlet temperature.

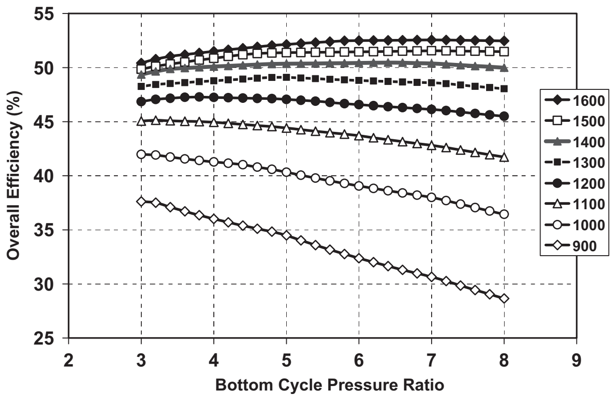


Fig. 15. The overall efficiency variation against bottoming-cycle pressure ratio for the EGT-ABC in various TITs ($R_c = 25$ and $T_0 = 25$ °C).

Table 4
Sensitivity of the cycle overall efficiency (%) to the processing parameters (TIT = 1400 °C, $T_0 = 25$ °C, $R_c = 25$ and $r_c = 6$).

	EGT-ABC	STIG-ABC	ABC	Simple GT
1% increase of TIT	0.450	0.302	0.416	−1.826
1% increase of R_c	0.023	0.051	0.124	0.249
1% increase of T_0	−0.437	−0.367	−0.443	0.796
1% increase of r_c	0.017	0.019	0.062	

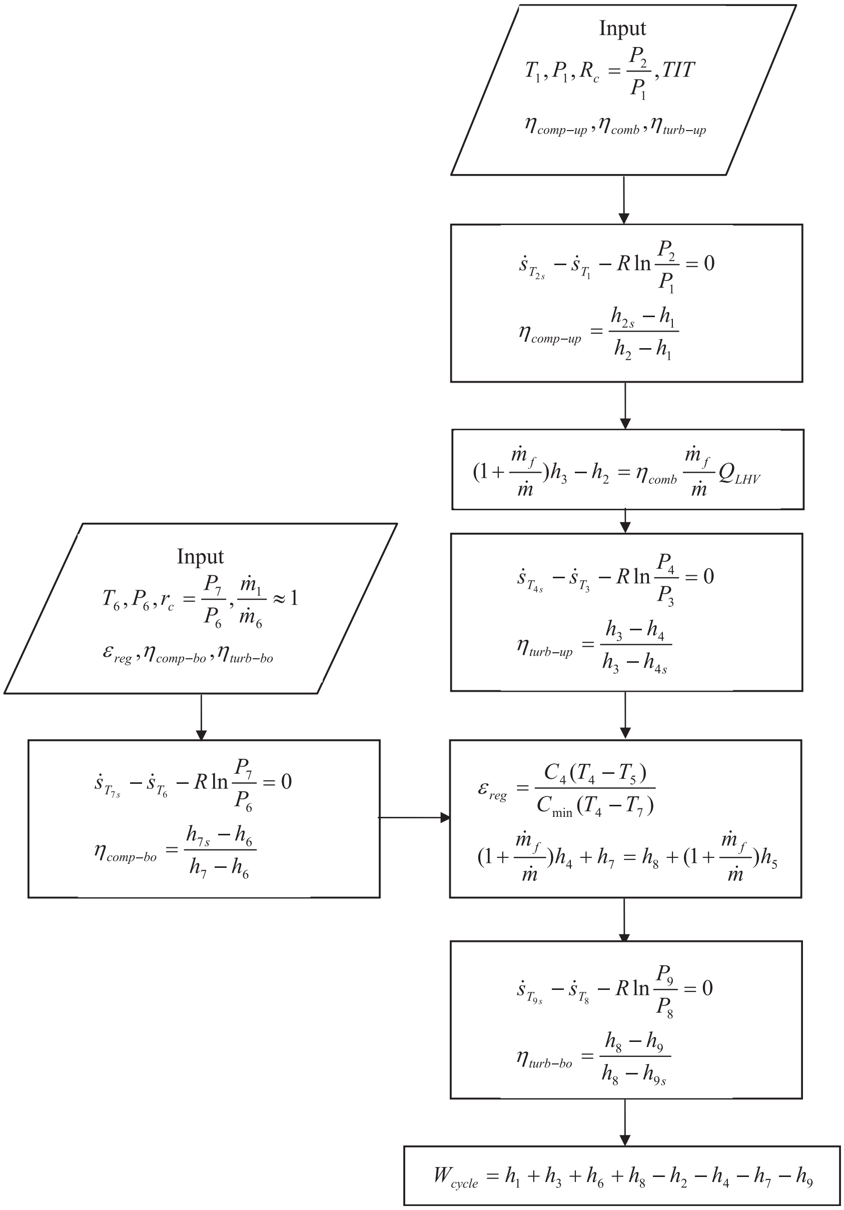
Table 5
Sensitivity of the cycle specific work (%) to the processing parameters (TIT = 1400 °C, $T_0 = 25$ °C, $R_c = 25$ and $r_c = 6$).

	EGT-ABC	STIG-ABC	ABC	Simple GT
1% increase of TIT	3.121	2.415	2.412	1.584
1% increase of R_c	−0.257	−0.171	−0.083	−0.157
1% increase of T_0	−1.324	−1.069	−1.134	−0.835
1% increase of r_c	0.017	0.019	0.062	

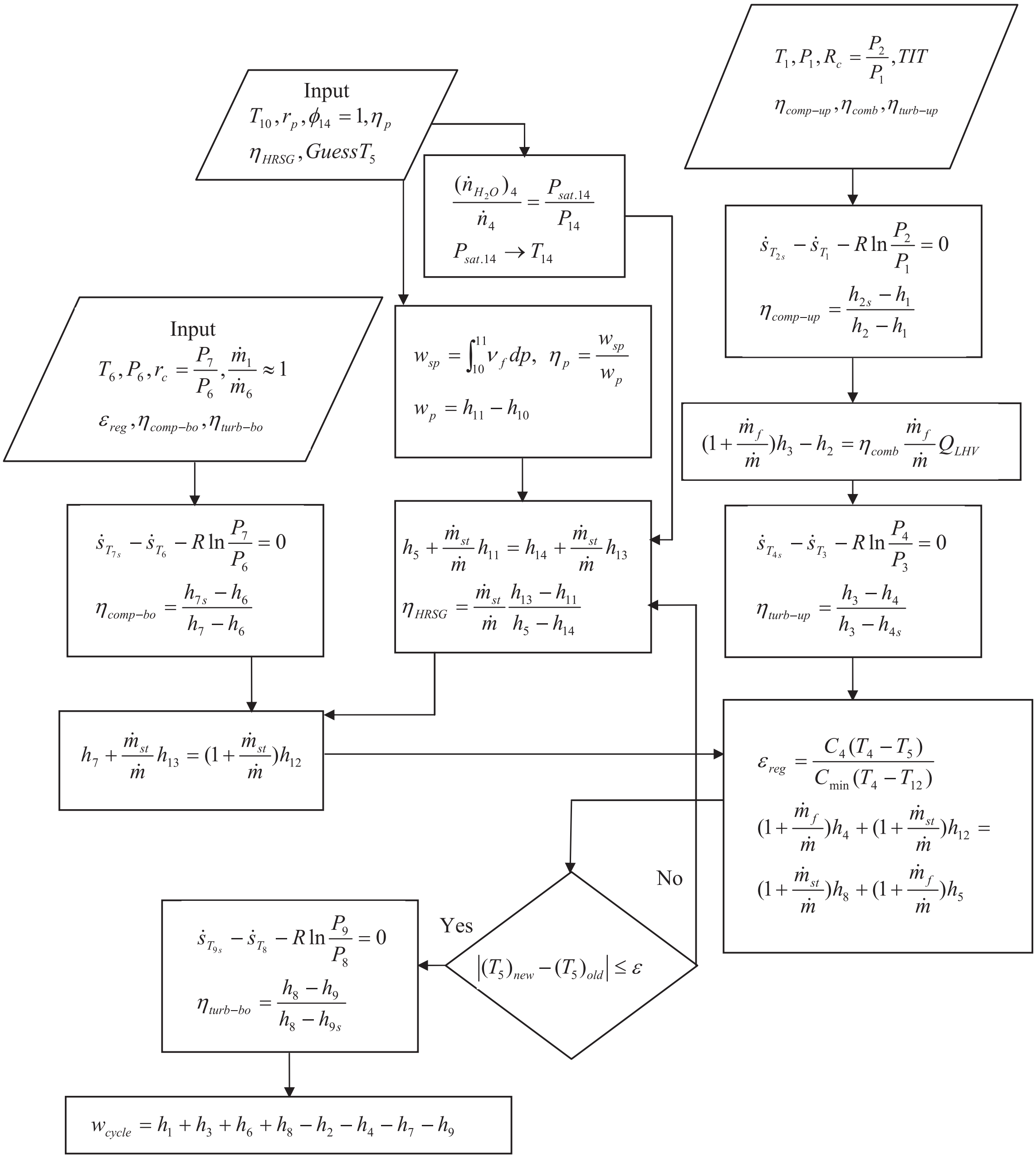
5. Conclusions

In this study, the effect of steam injection in a gas turbine cycle with the ABC has been investigated. Based on an exergy analysis, a computer program has been developed to investigate improving the performance of an ABC cycle. Several cycles are examined: the simple gas turbine, the ABC, 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 the EGT-ABC has a lower irreversibility and higher output work when compared to the STIG-ABC and ABC cycles. 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. For all cycles, the results of the model show that the overall efficiency is decreased as the ambient temperature is increased. For the EGT-ABC cycle, however, the reduction of the efficiency is minimal due to a higher opportunity of energy recovery.

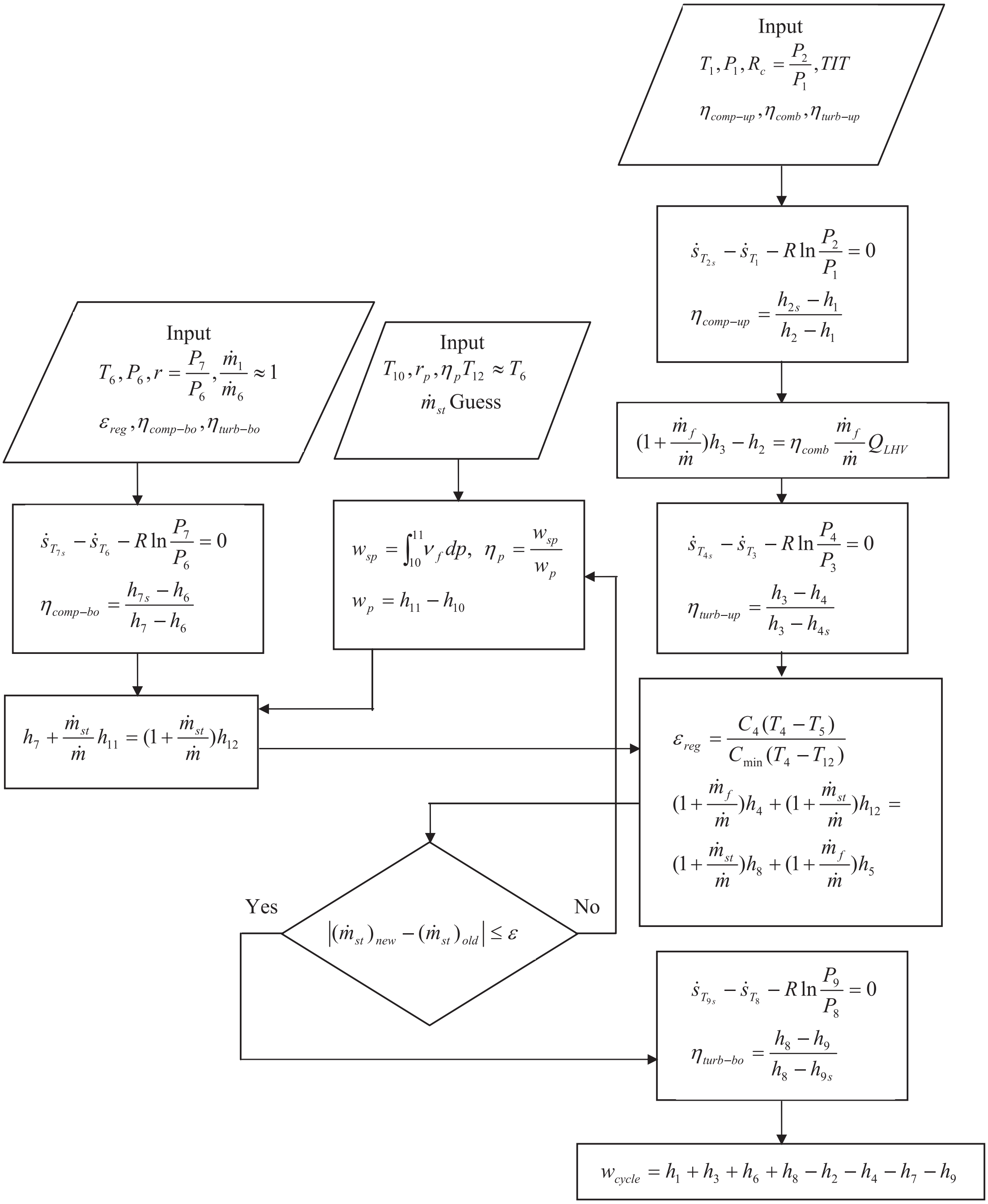
Appendix



Flowchart 1. Gas turbine with ABC calculation.



Flowchart 2. Gas turbine with STIG-ABC calculation.



Flowchart 3. Gas turbine with EGT-ABC calculation.

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