THERMAL PERFORMANCE of DIFFERENT GAS TURBINE CYCLES

ALY KAMEL ABD El-SAMED[1]

ABSTRACT

The performance of seven different gas turbine cycles are investigated versus the change of the gas turbine inlet temperature (TIT) which ranged from 773K to 1373K keeping ambient air temperature 294K, pressure ratio 9 and air flow rate 37 kg/s constant. The corresponding performances are expressed in terms of: fuel consumption rate, power output, thermal efficiency and specific power output for the seven cycles. From the results it is found that both of the turbine inlet temperature (TIT) and cycle arrangement have a great effect on the thermal performance of the gas turbine cycle. At the maximum turbine inlet temperature (TIT) 1373K, it is found that the highest obtainable power output is produced by the modified cycle 4 while the highest obtainable efficiency is produced by the modified cycle 6.

KEYWORDS: Gas Turbine, Performance, Power, Efficiency.

1. INTRODUCTION

The use of gas turbines in the power generation, power industry and petrochemical has increased very quickly in the last years. The last 20 years has seen a large growth in gas turbine technology. The growth is spearheaded by the growth of materials technology, new coatings and new cooling schemes. This, with the conjunction of increase in compressor pressure ratio, has increased the gas turbine thermal efficiency [1,2], from about 15% to 45% [3]. The performance of the power plant strongly depends on ambient air temperature. As the inlet air temperature decreases the power output and efficiency increases [4-10]. A parametric study of the effect of pressure ratio, ambient temperature, ambient relative humidity, effectiveness of the recuperated heat exchanger on the performance of gas turbine cycles are studied [11]. The study indicates that using two stages of cooling in the intercooler boost the gain in efficiency and applying absorption inlet cooling could increase the efficiency of the cycle by up to 6.6%. The power output of the gas turbine is a function of turbine inlet temperature which is fixed due to the metallurgical problem of turbine blade cooling. As the gas turbine inlet temperature increases the output power and efficiency increases [12,13].

The simple gas turbine itself is less efficient due to high temperature of the combustion gas leaving as exhaust from the turbine. This has led to the introduction of various modifications to the gas turbine design. Six different modified types/arrangements of gas turbine cycles are considered in this study. The performance of these cycles are calculated and determined versus the change of the turbine inlet temperature (TIT) from 500°C (773K) through 1100°C (1373K), which increases by increasing the fuel flow rate consumption. For the purpose of comparatively evaluation and analysis of the seven gas turbine cycles,

the simple Brayton gas turbine cycle is considered as the basis case. An existing small gas turbine power plant is considered as a source of the operating conditions, which are: air mass flow rate 37 kg/s, compressor pressure ratio 9 and calorific value of the fuel 41800 kJ/kg. The following parameters in Table-1 are calculated and derived based on the operating data of the simple gas turbine power plant taking into consideration the specific heat capacity of the flue gases and air are calculated as a function of the temperature [2,14].

Table-1

$\eta_{isentropic)compressor} = 82\%$	$\eta_{combustion\ chamber} = 95\%$
$\eta_{isentropic)gas\ turbine} = 85\%$	$\eta_{mechanical.}\ \eta_{electric\ generator} = 90\%$

Keeping the above operating conditions and the parameters in Table-1 constant, the performance of each gas turbine cycle is calculated using MATLAB software and expressed in terms of:
a) Fuel flow rate consumption,
b) Power output,
c) Thermal efficiency,
d) Work ratio,
e) Exhaust gas temperature,
f) Specific power output.

2. THE CONSIDERED GAS TURBINE CYCLES

Each of the considered gas turbines cycles (seven) is shown as a flow diagram and representation on T-s diagram accompanied with the related equations as follows:

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[1]*Mechanical Power Engineering Department, Faculty of Engineering, Port-Said University*

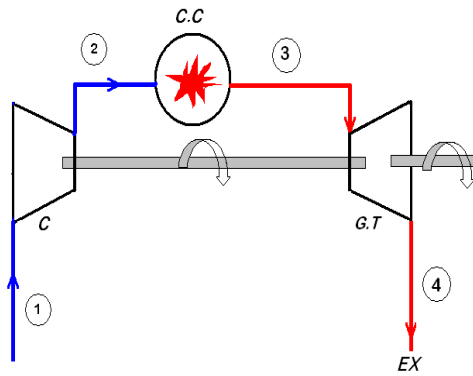## 2.1. The Simple Gas Turbine Cycle (Cycle1)

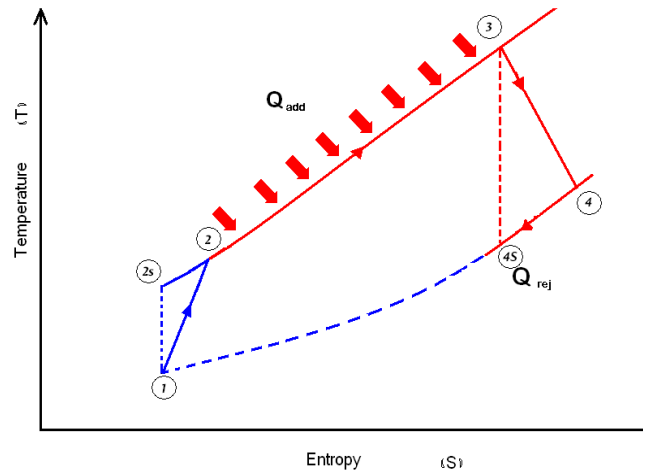**Fig.1(a) The Flow Diagram of the Simple Gas Turbine Cycle.**

Fig.1(b) Representation of The Simple Gas Turbine Cycle on T-S diagram.

The main equations are:

$$Power_{GT} = (\dot{m}_a + \dot{m}_f)\,C_{Pg}(T_4 - T_3) + \dot{m}_a C_{Pa}(T_2 - T_1) \qquad kW$$

$$Power_{net\,)GT} = [(\dot{m}_a + \dot{m}_f)\,C_{Pg}(T_4 - T_3) + \dot{m}_a C_{Pa}(T_2 - T_1)]\eta_{mech)GT}\eta_{EG} \qquad kW$$

$$\dot{mf} = \frac{(\dot{m}_a + \dot{m}_f)C_{Pg}T_3 - \dot{m}_a C_{Pa}T_2}{C.V.\times \eta_{cc}} \quad kg/s$$

$$\dot{Qadd} = (\dot{m}_a + \dot{m}_f)C_{Pg}T_3 - \dot{mia}C_{Pa}T_2 \quad kW$$

$$\eta_{th\,)GT} = \frac{-Power_{GT}}{\dot{Qadd}}$$

$$work\ ratio = \frac{-Power_{GT}}{-gross\ Power\ of\ Gas\ Turbine}$$

$$work\ ratio\ = \frac{-(\dot{m}_a + \dot{m}_f)[Cp_g(T_4 - T_3) + \dot{m}_a Cp_a(T_2 - T_1)]}{-[(\dot{m}_a + \dot{m}_f)Cp_g(T_4 - T_3)]}$$

$$Specific\ Power\ output = \frac{-Power_{net\,)GT}}{\dot{m}_f \times 3600} \quad kW.h/kg$$

The modified gas turbine cycles are as follows:

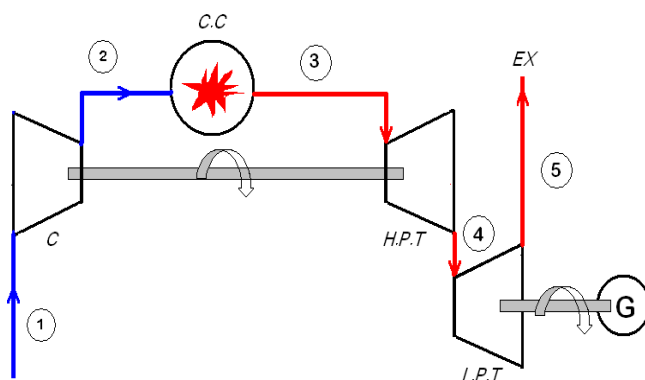## 2.2. The Simple Gas Turbine Cycle With Series Turbine (Cycle2)

Fig.2(a) The Flow Diagram of the Simple Gas Turbine Cycle with Series Turbine.
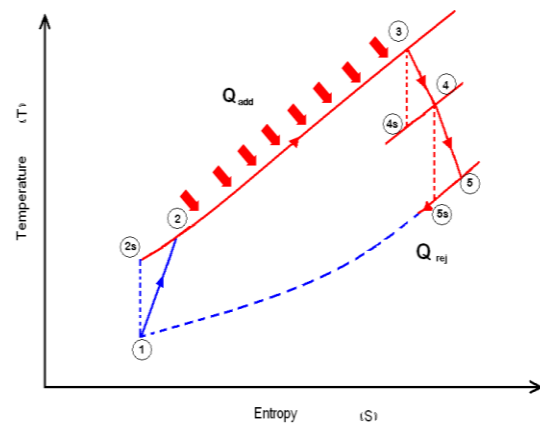
Fig.2(b) Representation of the Simple Gas Turbine Cycle with Series Turbine on " T – s" Diagram.

The complementary equations are:

$$Power_{net\,)GT} = (\dot{m}_a + \dot{m}_f)\,C_{Pg}(T_5 - T_4)\eta_{mech)GT}\eta_{EG} \qquad kW$$

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$$\eta_{\text{th})\text{GT}} = \frac{-Power_{GT}}{Q\dot{a}dd} = \frac{-(\dot{m}_a + \dot{m}_f)C_{P_g}(T_5 - T_4)}{(\dot{m}_a + \dot{m}_f)C_{P_g}T_3 - \dot{m}_a C_{P_a}T_2}$$

$$Work\ ratio = \frac{-Power_{GT}}{-gross\ power\ of\ gas\ turbines}$$

$$Work\ ratio = \frac{-(\dot{m}_a + \dot{m}_f)C_{P_g}(T_5 - T_4)}{-(\dot{m}_a + \dot{m}_f)[(C_{P_g}(T_4 - T_3) + C_{P_g}(T_5 - T_4)]}$$

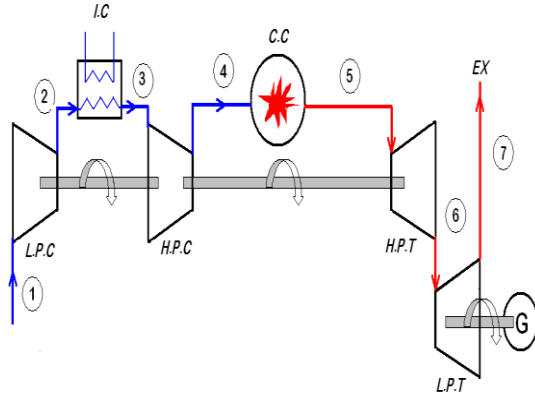## 2.3. The Simple Gas Turbine Cycle with Series Turbine and Two-Stages Compressor (Cycle 3)

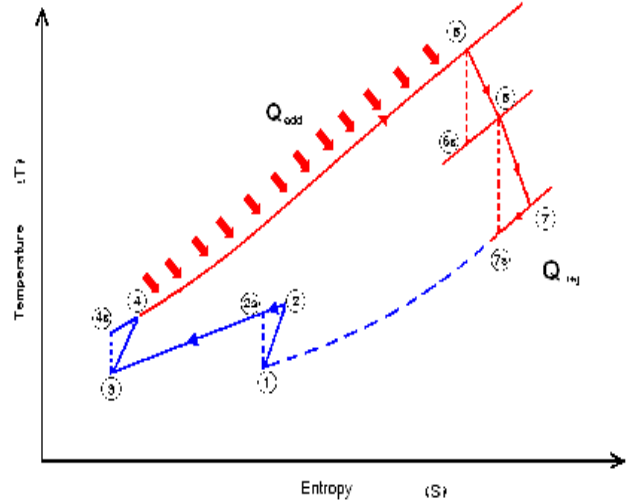**Fig.3 (a) The Flow Diagram of The Simple Gas Turbine Cycle with Series Turbine and two-stage Compressor.**

Fig.3(b) Representation of The Simple Gas Turbine Cycle with Series Turbine and two-stage Compressor on" T – S" Diagram.

The complementary equations are;

$$Power_{\text{net})\text{GT}} = (\dot{m}_a + \dot{m}_f)C_{P_g}(T_7 - T_6)\eta_{mech)\text{GT}}\eta_{EG} \qquad kW$$

2.4. The Simple Gas Turbine Cycle with Reheat and Two-Stage Compressor (Cycle 4)
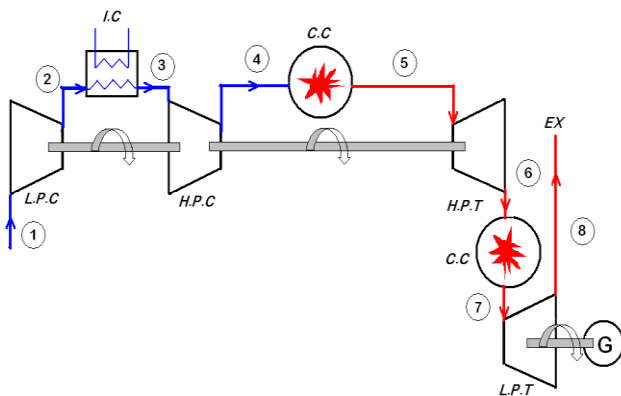
The complementary equations are:

Fig.4(a) The Flow Diagram Of The Simple Gas Turbine Cycle with Reheat and Two-Stage Compressor.
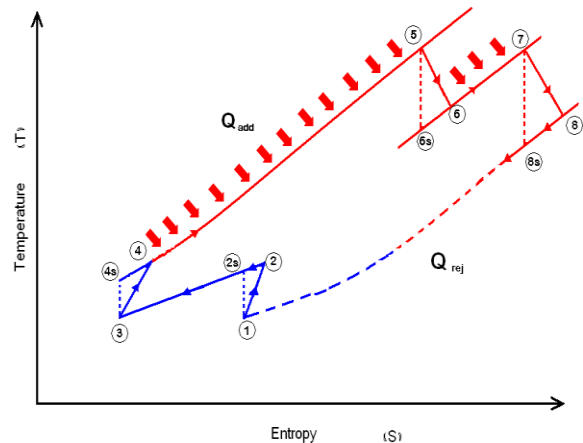
Fig.4(b) Representation of The Simple Gas Turbine Cycle with Reheat and Two-Stage Compressor on" T – S" Diagram .

$$\dot{m}_f = \dot{m}_{f1} + \dot{m}_{f2}$$

$$Power_{H.P.T} = (\dot{m}_a + \dot{m}_{f1})C_{P_g}(T_6 - T_5) = 2\dot{m}_a C_{P_a}(T_2 - T_1) \qquad kW$$

$$Power_{\text{net})\text{GT}} = (\dot{m}_a + \dot{m}_{f1} + \dot{m}_{f2})C_{P_g}(T_8 - T_7)\eta_{mech)\text{GT}}\eta_{EG} \qquad kW$$

$$\eta_{\text{th})GT} = \frac{-Power_{GT}}{Q\dot{a}dd} = \frac{-(\dot{m}_a + \dot{m}_{f1} + \dot{m}_{f2})C_{P_g}(T_8 - T_7)}{(\dot{m}_a + \dot{m}_{f1})C_{P_g}T_5 - \dot{m}_a C_{P_a}T_4 + (\dot{m}_a + \dot{m}_{f1} + \dot{m}_{f2})C_{P_g}T_7 - (\dot{m}_a + \dot{m}_{f1})T_6)}$$

2.5. The Simple Gas Turbine Cycle with Series Turbine and Two-Stage Compressor and Heat Exchanger (Cycle5)
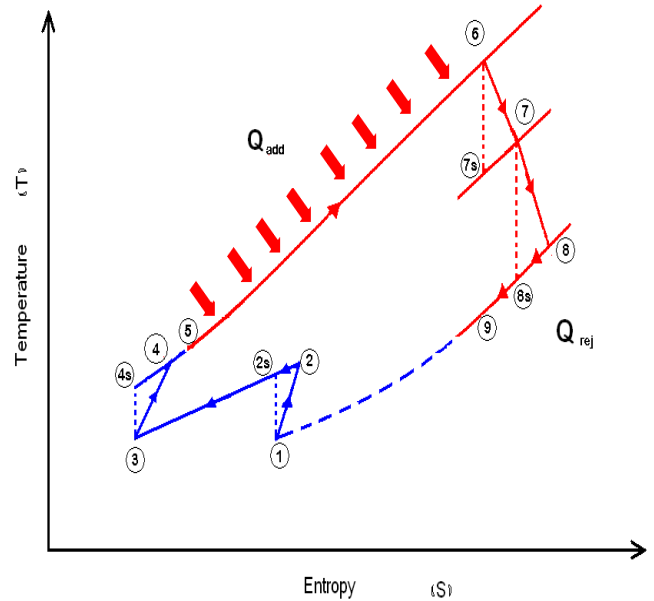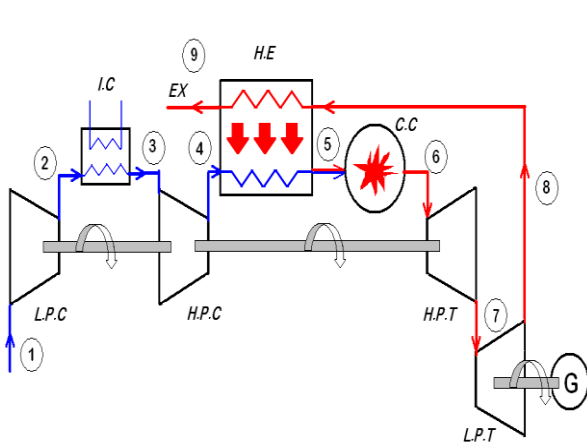

Fig.5(a) The Flow Diagram of The Simple Gas Turbine Cycle with Series Turbine and two-stage Compressor and Heat Exchanger.

Fig.5(b) Representation of The Simple Gas Turbine Cycle with Series Turbine and two-stage Compressor and Heat Exchanger on" T–S" Diagram.

From the literature survey, the mean value of the heat exchanger effectiveness is taken 0.72 [2,3] and considered to be constant for the different cycles.

The complementary equations are:

$$T_3 = T_1 \ , T_4 = T_2 \ , T_6 = T_{max}$$

$$Effectiveness = \frac{\dot{m}_a C_{p_a}(T_5 - T_4)}{(\dot{m}_a + \dot{m}_f) C_{p_g}(T_8 - T_4)}$$

Heat balance for heat exchanger;

$$\dot{m}_a C_{p_a}(T_5 - T_4) = (\dot{m}_a + \dot{m}_f) C_{p_g}(T_8 - T_9)$$

$$Power_{\text{net })GT} = (\dot{m}_a + \dot{m}_f)C_{P_g}(T_8 - T_7)\eta_{mech)GT}\eta_{EG} \qquad kW$$

$$\eta_{\text{th})GT} = \frac{-Power_{GT}}{Q\dot{a}dd} = \frac{-(\dot{m}_a + \dot{m}_f)C_{P_g}(T_8 - T_7)}{(\dot{m}_a + \dot{m}_f)C_{P_g}T_6 - \dot{m}_a C_{P_a}T_5}$$

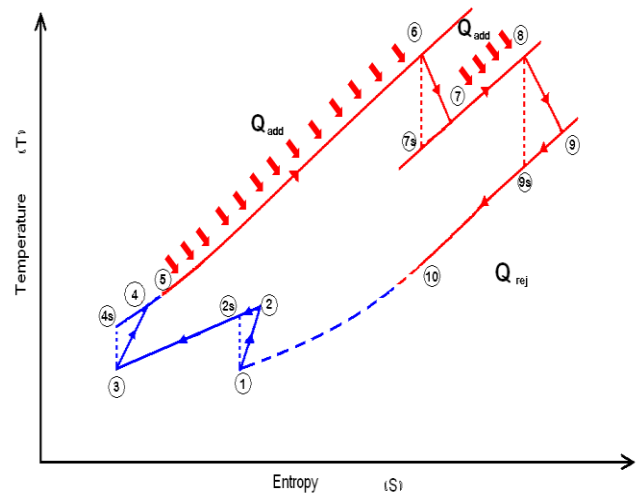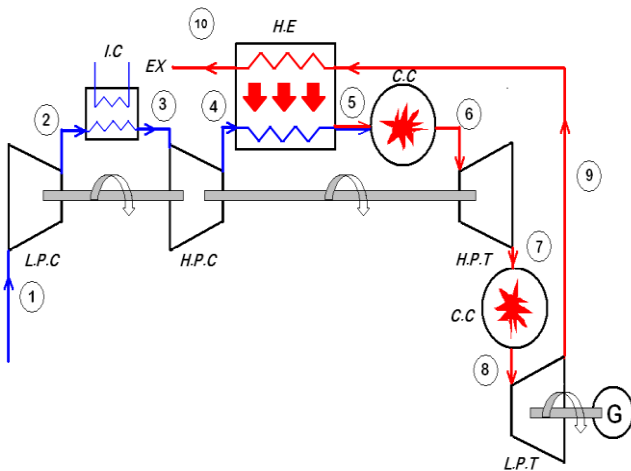## 2.6. The Simple Gas Turbine Cycle with Reheat and Two-Stage Compressor and Heat Exchanger (Cycle6)

Fig.6(a) The Flow Diagram of The Simple Gas Turbine Cycle with Reheat and Two-Stage Compressor and Heat Exchanger.

Fig.6(b) Representation of The Simple Gas Turbine Cycle with Reheat and Two-stage Compressor and Heat Exchanger on "T–S" Diagram.

The complementary equations are:

$$T_6 = T_8 = T_{max}$$

Heat balance for heat exchanger;

$$\dot{m}_a C_{p_a}(T_5 - T_4) = (\dot{m}_a + \dot{m}_{f1} + \dot{m}_{f2})C_{p_g}(T_9 - T_{10})$$

$$\dot{m}_f = \dot{m}_{f1} + \dot{m}_{f2}$$

$$Power_{net)GT} = (\dot{m}_a + \dot{m}_{f1} + \dot{m}_{f2})C_{P_g}(T_9 - T_8)\eta_{mech)GT}\eta_{EG} \qquad kW$$

$$\eta_{th)GT} = \frac{-Power_{GT}}{\dot{Q}add} = \frac{-(\dot{m}_a + \dot{m}_{f1} + \dot{m}_{f2})C_{P_g}(T_9 - T_8)}{(\dot{m}_a + \dot{m}_{f1})C_{P_g}T_6 - \dot{m}_a C_{P_a}T_5 + (\dot{m}_a + \dot{m}_{f1} + \dot{m}_{f2})C_{P_g}T_8 - (\dot{m}_a + \dot{m}_{f1})C_{P_g}T_7}$$

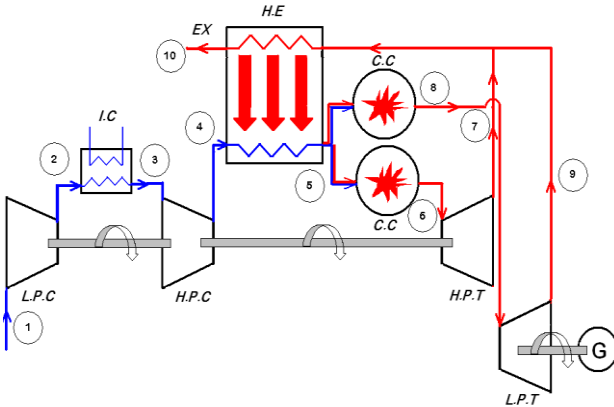## 2.7. The Parallel Flow Gas Turbine Cycle with Two-Stage Compressor and Heat Exchanger (Cycle7)

Fig.7(a) The Flow Diagram of The Parallel Flow Gas Turbine Cycle with Two-Stage Compressor and Heat Exchanger.
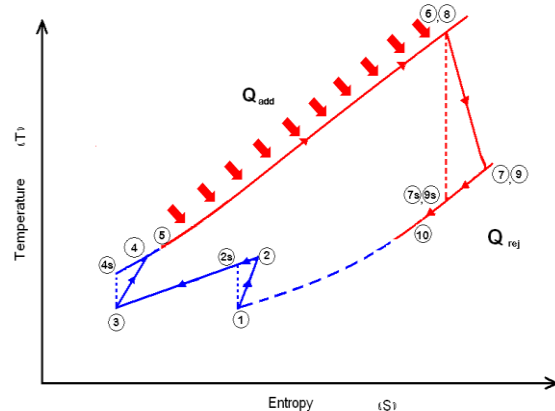
Fig.7(b) Representation of The Parallel Flow Gas Turbine Cycle with Two-Stage Compressor and Heat Exchanger on" T– S" Diagram .

The complementary equations are:

$$T_6 = T_8 = T_{max}$$
$$T_7 = T_9$$
$$\dot{m}_a = \dot{m}_{a)cc1} + \dot{m}_{a)cc2}$$
$$Power)_{net\ GT} = (\dot{m}_{a)cc2} + \dot{m}_{f)cc2}) C_{P_g} (T_9 - T_8)\eta_{mech)GT}\eta_{EG} \qquad kW$$

$$\eta_{th)GT} = \frac{-Power)_{Gt}}{Q_{add}} = \frac{-(\dot{m}_{a2} + \dot{m}_{f2}) C_{P_g}(T_9 - T_8)}{((\dot{m}_{a)cc1} + \dot{m}_{f)cc1})C_{P_g}T_6 - \dot{m}_{a)cc1}C_{P_a}T_5) + (\dot{m}_{a)cc2} + \dot{m}_{f)cc2})C_{P_g}T_8 - \dot{m}_{a)cc2}C_{P_a}T_5}$$

3. RESULTS

3.1. Fuel Consumption of the Different Gas Turbine Cycles

The increase of the turbine inlet temperature is occurred as a result of increasing the fuel consumption rate (keeping the air mass flow rate constant). Figure 8(a) shows that, as the turbine inlet temperature increases from 737K to 1373K, the corresponding comparatively required mass flow rate consumption for all the gas turbine cycles increases gradually with straight line relations. Generally, for the different turbine inlet temperatures the lowest fuel consumption rates are found to be for the gas turbine cycle7 and cycle5, while the highest values is found to be for cycle4. At turbine inlet temperature 1373K the lowest fuel consumption rates are found to be 0.603 kg/s and 0.61 kg/s for cycle7 and cycle5 respectively while the

highest value 1.24 kg/s is found to be for cycle4 as clearly shown in Fig.8(b). So, at the maximum turbine inlet temperature 1373K the fuel consumption rate of cycle1 (i.e. the basis simple gas turbine cycle) can be reduced due to the effect of adding the heat exchanger by 25%, 12% and 26% if cycle 5, cycle 6 and cycle 7 are applied.

3.2. Power Output of the Different Gas Turbine Cycles

As the turbine inlet temperature increases from 773K to 1373K, the net power output of the gas turbine cycles increases gradually in straight lines relations as shown in Fig.9(a) where their descending order are as follows; cycle4, cycle6, cycle3, cycle5, cycle7, cycle1, and cycle2. The highest comparative value is found to be for cycle4 where it increases from 4 MW to 14.2

MW while for cycle 1 increases from 200 kW to 9.1 MW.

Running the gas turbine cycles at the maximum turbine inlet temperature 1373K, produce the highest values of the power output of 14.2 MW for cycle 4 and 12.7 MW for cycle 6 while for cycle 1 the power output is 9.1 MW. That means applying the modified cycle 4 and cycle 6 leads to an increase of power output by 56% and 39.56% respectively.

3.3. Thermal Efficiency of the Different Gas Turbine Cycles

As the turbine inlet temperature increases from 773K to 1373K, it can be noticed from Fig.10(a) that, the thermal efficiency of the gas turbine cycles significantly increases in the form of two groups. For the first group which includes cycle 3, cycle 4, cycle 1, and cycle 2 their thermal efficiencies increase slightly while for the second group which includes cycles 6, 5, and 7 their thermal efficiencies increase significantly producing the highest values. Figure 10(b) shows that the highest values of 46.0%, 43.5%, 41.86% are corresponding to cycle 6, cycle 5, and cycle 7 respectively when running at maximum inlet temperature 1373K, while the thermal efficiency for cycle 1 is low 28.57%. So, the thermal efficiency of the simple gas turbine cycle (cycle 1) can be increased by 61.0%, 52.26%, and 46.52% if cycle 1 modified to become cycle 6, cycle 5, or cycle 7 respectively.

3.4. Work Ratio of the Different Gas Turbine Cycles

The work ratio is a term which deals with the negative effect of the compressor work on the power output. As expected, the trend and the order of the work ratio for the different gas turbine cycles versus the turbine inlet temperature is the same trend and the same order of the power output as shown in Figs.11(a), 11(b) compared with 9(a), 9(b). At the maximum turbine inlet temperature 1373K, the highest comparatively work ratio of 0.58 is found to be for cycle 4 where its power output is also the highest value of 14.2 MW.

3.5. Exhaust Gas Temperature of the Different Gas Turbine Cycles

As the turbine inlet temperature increases from 773K to 1373K, the exhaust gas temperature increases with straight lines relations. Again, there are two groups; the first group represents cycle 6, cycle 7, and cycle 5 where the incremental increase of the exhaust temperature are small (by about 95K) while for the second group which represents the rest of the cycles, the incremental increase are big (about 390K) as shown in Figs.12(a). That means for the first group, heat losses with the exhaust gases are smaller than those of the second group leading to higher thermal efficiency as seen in Fig.10(a,b). The highest exhaust gas temperature leaving the turbine is found to be 1032K for cycle 4 as shown in Fig.12(b), that explain why the thermal efficiency of this cycle 4 is low 28.6% (which equal to the thermal efficiency of the simple basis cycle).

3.6. Specific Power Output of the Different Gas Turbine Cycles

Generally, the specific power output for the different gas turbine cycles increases as the turbine inlet temperature increases from 773K to 1373K as shown in Fig.13(a). At turbine inlet temperature 950K and above, it is noticed that the highest values of specific power output are found to be for cycle 6, cycle 5, and cycle 7 respectively. At the maximum turbine inlet temperature 1373K the highest specific power output of 4.93 kW.h/kg is found to be for cycle 6, while at the same temperature the minimum values of 3.08, 3.08, and 2.85 kW.h/kg are found to be for cycle 1, cycle 4 and cycle 2 respectively as shown from Fig.13(b). Also, from Fig.13(a) it can be noticed that the curves divided into two groups; the first group includes cycles 5,6,7 while the second group includes cycles 1,2,3,4. As TIT increases the specific power output of the first group cycles increases significantly and proportionally but for the second group it increases slightly and will be nearly constant above 1373K –by extrapolation. So, it is recommended to modify the simple cycle 1 to become cycle 6 that will lead to an increase of the specific power output by 61%.

4. CONCLUSIONS

1. The thermal performance curves of the seven different gas turbine cycles are obtained.
2. As the turbine inlet temperature (TIT) increases from 773K to 1373K the power output, the thermal efficiency and the specific power output increase for the seven cycles and reach their maximum values at 1373K.
3. The highest thermal efficiency and the highest specific power output are found to be for the modified cycle 6 as their values increase from 12.5% to 46% and from 1.34 kW.h/kg to 4.93 kW.h/kg as the turbine inlet temperature increases from 773K to 1373K respectively. In other words at TIT 1373K both of the thermal efficiency and the specific power output of the modified cycle 6 increase by 61% referred to cycle 1.
4. Increasing the turbine inlet temperature as well as modifying the simple gas turbine cycle both of them have a great effect on increasing the power output, thermal efficiency and specific power output of the gas turbine cycles.

NOMENCLATURE

w = work, kJ/kg
$\dot{m}$ = flow rate, kg/s
η = efficiency, %
C_P = specific heat capacity, kJ/kg.K
T = temperature, K
q = specific heat, kJ/kg
Q = heat rate, kJ/s
EX = exhaust gases
L.P.C. = Low pressure compressor
H.P.C. = High pressure compressor
I.C. = inter cooler
H.E. = heat exchanger
TIT = Turbine Inlet Temperature, K

SUBSCRIPTS
GT = gas turbine
g= gas
a= air
f=fuel
add= addition
mech= mechanical
EG= electric generator
H.P.T.= high pressure turbine
L.P.T.= low pressure turbine
CC= combustion chamber
rej=reject
th=thermal

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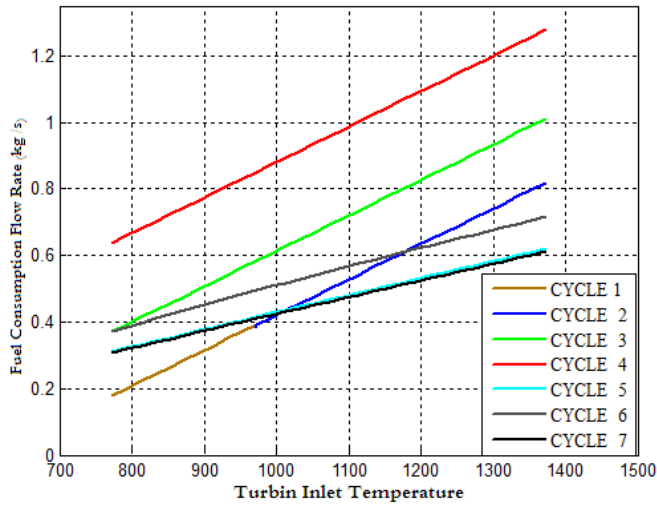
Fig. 8 (a) Represents The Effect Of Changing The
Turbine Inlet Temperature On The Fuel Consumption
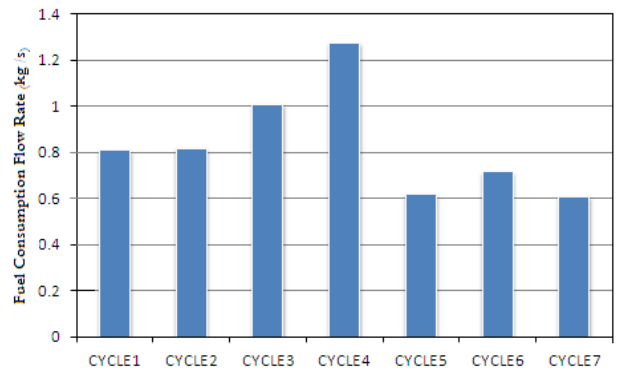Flow Rate Of The Different Gas Turbin cycles

Fig. 8 (b) Represents The Maximum Fuel er
Consumption Flow Rate Values Of The Different
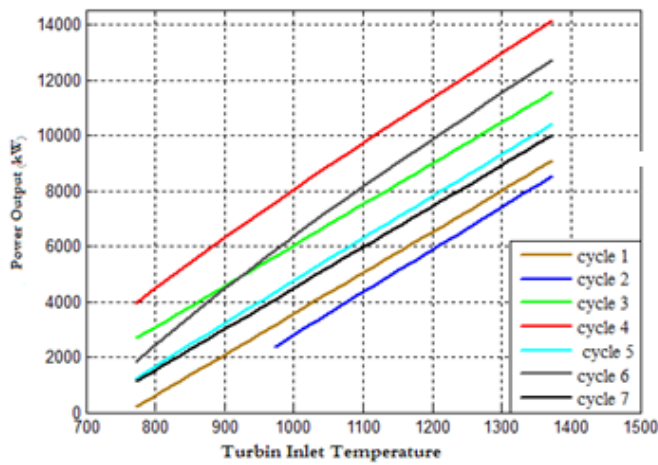Gas Turbine Cycles At T_{gas} =1373k

Fig. 9 (a) Represents The Effect Of Changing The
Turbine Inlet Temperature On The Power
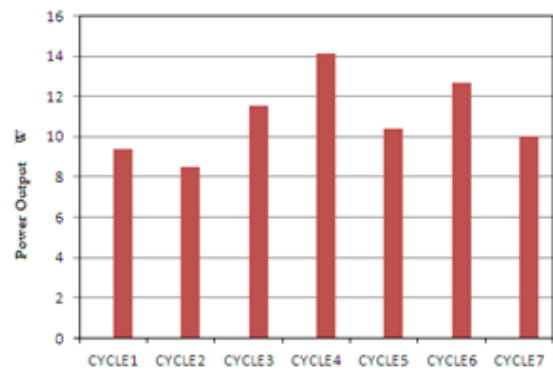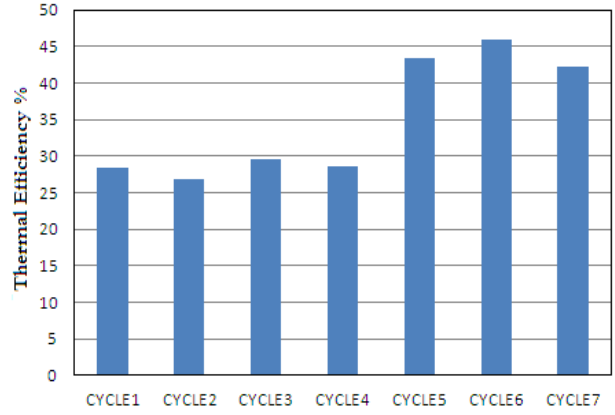Output Of The Different Gas Turbin cycles

Fig. 9 (b) Represents The Maximum Power
Output Values Of The Different
Gas Turbine Cycles At T_{gas} =1373k

66
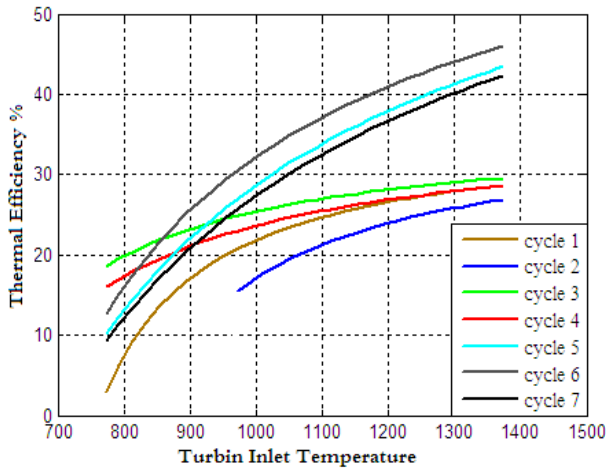
Fig. 10(a) Represents The Effect Of Changing The
Turbine Inlet Temperature On The Thermal
Efficiency Of The Different Gas Turbin cycles

Fig.10(b) Represents The Maximum Thermal
Efficiency Values Of The Different
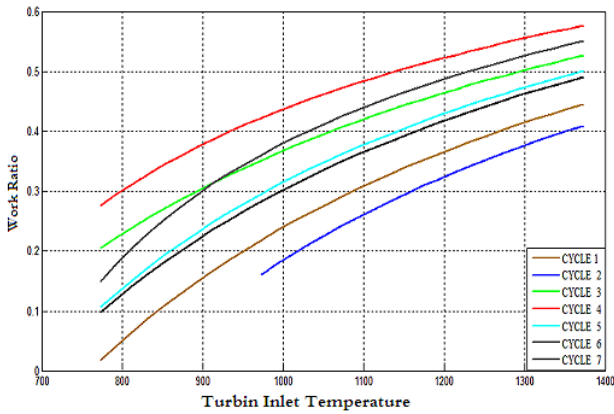Gas Turbine Cycles At T_{gas} =1373k

Fig. 11(a) Represents The Effect Of Changing The
Turbine Inlet Temperature On The Work
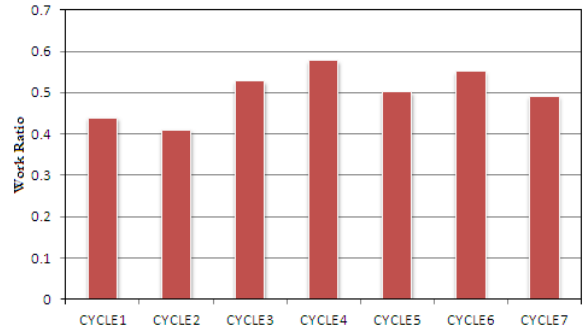Ratio Of The Different Gas Turbin cycles

Fig.11(b) Represents The Maximum Work Ratio
Values Of The Different Gas Turbine
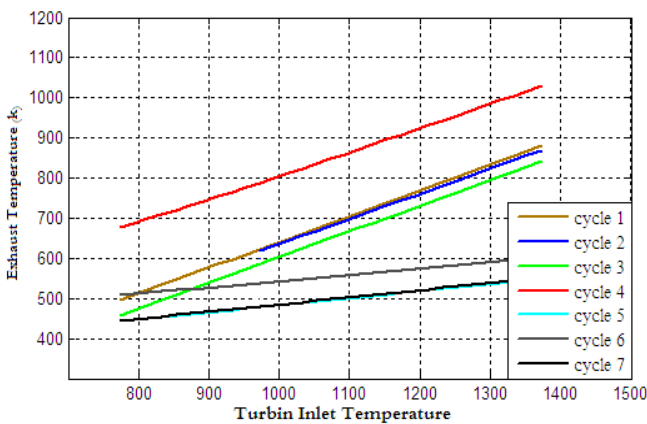Cycles At T_{gas} =1373k

Fig. 12(a) Represents The Effect Of Changing The
Turbine Inlet Temperature On The Exhaust
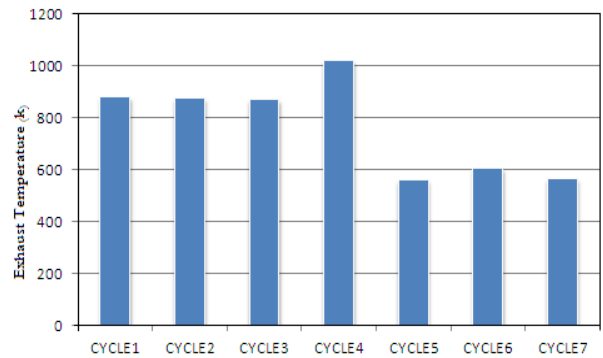Temperature Of The Different Gas Turbin cycles

Fig. 12(b) Represents The Maximum Exhaust
Temperature Values Of The Different
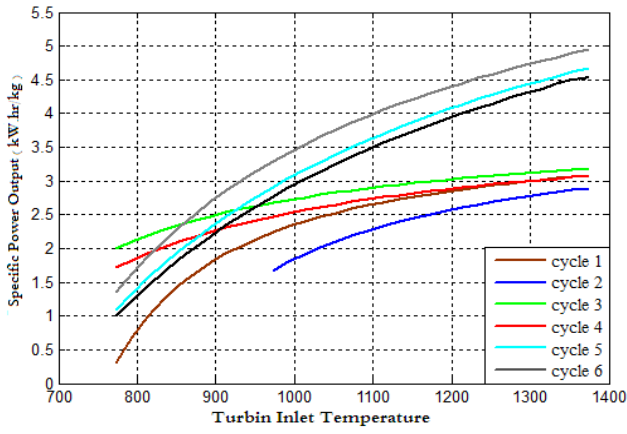Gas Turbine Cycles At T_{gas} =1373k

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Fig. 13 (a) Represents The Effect Of Changing The Turbine Inlet Temperature On The Specific Power Output Of The Different Gas Turbin cycles
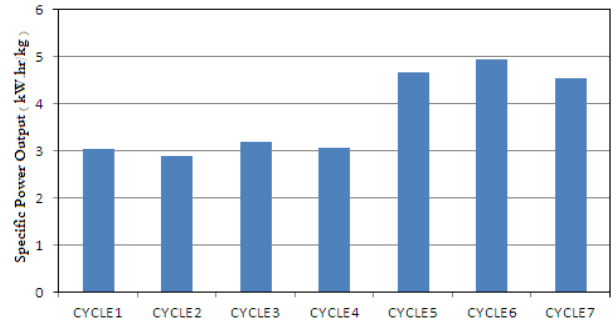

Fig. 13 (b) Represents The Maximum Exhaust Temperature Values Of The Different Gas Turbine Cycles At T_{gas} =1373k