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Thermal Performance Enhancement of a Practical Combined Gas-Steam Power Plant

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Abstract

The research suggests some means to increase the very low overall efficiency and power output of existing combined plant. The effect of changing some operating parameters on the performance of the combined plant is investigated. Optimum operating conditions are chosen to be run together lead to an increase of the net power output by 25.03% and the overall efficiency by 7.28%. Good correlations are obtained correlating the net power output and overall efficiency of the combined plant with the operating parameters.

Keywords: Gas-Turbine, Steam-Turbine, Combined Plant, Operating Parameters.

1. INTRODUCTION

The gas and steam turbines are the greatest means to generate mechanical power. Both gas and steam turbines have been successfully working in large scale to generate the electricity. Combining the gas and steam cycles results in higher efficiency. The gas turbine using Brayton cycle and the steam power system using Rankine cycle are two such cycles that complement each other to form efficient combined cycle. The Brayton cycle has a high source temperature and rejects heat at a temperature such that it used as energy source for the Rankine cycle in a combined cycle. The heat recovery steam generator is one of the most important components of the combined cycle power plant. That significantly affects the efficiency. A typically high thermal efficiency of combined cycles ranged 50-60% is achieved [1,2]. The development in gas-turbine technology, as well as increases in steam-turbine cycle temperature and pressure, heat recovery steam generator design enhancement is expected to achieve further combined plants efficiency improvement [3,4]. Also, the effect of various parameters like pinch point, steam pressure, steam temperature, and gas flow rate on the performance of the heat recovery steam generator are investigated [5]. Thermodynamic analysis of a combined cycle power plant with a supplementary firing system is investigated [6]. Alternative arrangements for improving the efficiency of the combined cycle is found that, reheat improves the cycle efficiency by 0.2-0.4% compared to non-reheat cycles [7]. The dual pressure heat recovery steam generator have been widely used because they showed higher efficiency than single pressure systems and lower investment cost than triple pressure [8,9]. The maximum efficiency of the combined cycle is found to be at pressure ratio of 18 at the turbine inlet temperature 1400K [10].

In the present work, parametric thermodynamic analysis of a practical combined gas-steam power plant is undertaken. The proposed power plant established and has been operated since 2010. Unfortunately, the maximum obtainable power is 570.669 MW and the maximum calculated overall efficiency is found to be 38.59% which is very low compared to the practical values which ranged from 50% to 60% [1,2]. Re-evaluation of the effect of changing –in turn [11]- the operating parameters on the power plant performance is investigated in order to try to increase the power output and overall efficiency. The operating parameters include: the maximum gas temperature (which is a function of the fuel mass flow rate consumption), inlet air temperature, pressure ratio, and mass flow rate fraction of the low pressure steam. The performance of the plant is expressed in terms of: power out and efficiency of gas cycle, steam cycle and combined plant, specific power output, the dryness fraction of the exhaust steam and exhaust gas temperature. Also, the effect of adding supplementary firing unit on the combined plant performance is investigated.

For the combined plant each two gas turbine units supply their gases to operate one steam turbine unit as shown from the flow diagram of the plant in Fig.1. The gas turbine unit is a simple cycle burns with natural gas. The steam cycle consists of two stages turbine (high and low pressures turbines), a de-aerator, and a dual pressure heat recovery steam generator.

The basic operating data of the gas-turbine, steam-turbine, and combined plant (the case study) are presented and described in Table.1 as collected, derived and calculated for the power plant.

The effect of make-up steam and gland steam condenser is ignored. The specific heat capacity of the gas is calculated as a function of the gas temperature and mass fraction of the combustion products constituents consequently, the basic $Cp)_g$ is found to be 1.05 KJ/Kg.K. Applying the thermodynamics relations of the perfect gas and energy balance equations for each element of the combined power plant yields: the gas temperatures, steam enthalpies and extracted steam mass flow rate which be used to calculate the

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performance of the plant using MATLAB software according to the following main equations (see the flow diagram in Fig.1 for the following calculations)

Table-1

Air mass flow rate for the two gas turbines = 1572.6 kg/s	$T_{\text{inlet air temperature}}$ = 22°C
Specific heat capacity of air $C_{p)air}$= 1.005 kJ/kg.K	Pressure ratio of the air compressor = 16.9
γ_{air} = 1.4	Compressed air temperature = 414°C
Fuel mass flow rate for the two gas turbines = 30 kg/s	Gas temperature inlet to gas-turbine =1219°C
Total gases flow rate = 1602.6 kg/s	Exit gas temperature of gas turbine = 597°C
Calorific value of natural gas= 49291 kJ/kg	Exhaust gas temperature =230°C
$Total\ steam\ mass\ flow\ rate$ = 210 kg/s	High pressure live steam = 90 bar
$(\dot{m}_{L.P.Steam} / \dot{m}_{Total\ .Steam})\% = 30\%$	Low pressure live steam = 4.4 bar
$\eta_{\text{combustion chamber}} = \eta_{\text{combustion Supplementary}} = 96.36\%$	Temperature of high pressure live steam = 508°C
$\eta_{\text{heat recovery steam generator}} = 89.33\%$	Temperature of low pressure live steam = 254°C
$\eta_{\text{Mechanical)pump}} = 97\%$	Exit temperature of high pressure steam turbine = 216°C
$\eta_{\text{Mechanical)Gas Turbine}} = 98\%$	De-aerator pressure = 1.69 bar
$\eta_{\text{Mechanical)Steam Turbine}} = 98\%$	Inlet temperature to low pressure steam turbine after mixing point = 227°C
$\eta_{\text{Steam)generator}} = 99\%$	χ (steam dryness fraction) = 0.93
$\eta_{\text{GasTurbine)generator}} = 98\%$	Pressure of steam condenser = 0.05 bar
$\eta_{\text{isentropic of compressor}} = 92\%$	Effectiveness of the heat recovery steam generator = 0.68
$\eta_{\text{isentropic of gas turbine}} = 87\%$	Power output of the two gas turbines = 394.962MW
$\eta_{\text{isentropic of high pressure steam turbine}} = 74\%$	Power output of the two stages steam turbines = 175.707MW
$\eta_{\text{isentropic of low pressure steam turbine}} = 70\%$	Power output of the combined plant =570.669MW

$$Power_{compressor} = \dot{m}_a Cp_a (T_2 - T_1) \quad KW \qquad \ldots(1)$$

$$\eta_{CC} = \frac{\dot{m}_g\ Cp_g T_3 - \dot{m}_a\ Cp_a T_2}{\dot{m}_{fuel\ )cc} \times C.V.} \qquad \ldots(2)$$

$$Power_{GT} = \dot{m}_g Cp_g (T_4 - T_3) \quad KW \qquad \ldots(3)$$

$$Power_{GT)net} = Power_{GT} + Power_{Compressor} \quad KW \qquad \ldots(4)$$

$$\dot{Q}add = \dot{m}_g\ Cp_g T_3 - \dot{m}_a\ Cp_a T_2 \quad KW \qquad \ldots(5)$$

$$\eta_{\text{thermal)GT}} = \frac{-Power_{\ GT\ )\ net}}{Qadd} \qquad \ldots(6)$$

$$Power_{output\ )GT} = (Power_{GT} + Power_{Compressor})\eta_{mec\ hGT}\,\eta_{EG} \quad KW \qquad ..(7)$$

$$\eta_{steam\ \ generator} = \frac{\dot{m}_{steamHP}\ (h_6 - h_{14}) + \dot{m}_{steamLP}\ (h_7 - h_{13})}{\dot{m}_g\ Cp_g (T_4 - T_5)} \qquad \ldots(8)$$

$$Power_{HPT} = \dot{m}_{steamHP}\ (h_8 - h_6) \qquad KW \qquad \ldots(9)$$

$$Power_{LPT} = \dot{m}_{steamLP}\ (h_{10} - h_9) \qquad KW \qquad \ldots(10)$$

$$Power_{ST} = Power_{HPT} + Power_{LPT} \qquad KW \qquad \ldots(11)$$

$$Power_{ST)\,net} = \left[Power_{ST} \,.\, \eta_{mec\ hST} + \frac{Power_{\ SP}}{\eta_{mec\ hP}}\right] \qquad KW \qquad \ldots(12)$$

$$\eta_{\text{thermal }\ )\text{ST}} = \frac{-Power_{\ ST\ )\ net}}{\dot{m}_{\ steamHP}\ (h_6 - h_{14}) + \dot{m}_{steamLP}\ (h_7 - h_{13})} \qquad \ldots(13)$$

$$Power_{output\ \ )\ ST} =$$
$$\left[Power_{ST} \,.\, \eta_{mec\ hST} + \frac{Power_{\ SP}}{\eta_{mec\ hP}}\right] .\, \eta_{EG} + Power_{auxiliary} \qquad KW \qquad \ldots \qquad .\,(14)$$

$$Power_{output\ \ )combined\ \ \ plant} = Power_{output\ \ )GT} + Power_{output\ \ )\ ST} \qquad KW \qquad \ldots\ldots(15)$$

$$\eta_{overall\ \ )\text{combined}\ \ \ \text{plant}} = \frac{-Power_{\ output\ \ )combined\ \ \ plant}}{fuel\ \ consumption\ \ \ rate\ \times calorific\ \ \ value} \qquad \ldots..(16)$$

$$Specific\ Power\ Output = \frac{-Power_{\ output\ \ )combined\ \ \ plant}}{fuel\ \ consumption\ \ \ rate} \qquad MW.s/Kg \qquad \ldots\ldots(17)$$

$$Extra\ heat\ added\ in\ supplementary\ firing\ system = m_{fuel}{}^{\cdot}{}_{\ extra} \times C.V. \times \eta_{cs} \ldots..(18)$$
$$= m_{g)}{}^{\cdot}_{total}\ Cp_g (T_g - T_4)$$

Where,
$m_{gas\ )total}$ = air flow rate + fuel rate in combustion chamber + extra fuel rate
$\dot{m}$ = mass flow rate
T = temperature
η = efficiency
h = steam enthalpy
Cp= specific heat capacity
C.V. = calorific value of fuel (Natural Gas)
Q = heat flow rate

subscripts
a = air
g = gas
cc = combustion chamber
HP = High pressure
LP = Low pressure
HPT = High pressure turbine
LPT = Low pressure turbine
cs =combustion in supplementary
EG= electric generator
GT = gas turbine
ST = steam turbine
SP = steam pumps

2. RESULTS

From the collected operating data of the practical combined plant, it is found that the produced net power output is 570.669 MW and the calculated overall efficiency of the plant is 38.59% which unfortunately less than the expected range 50-60% [1,2]. That may be due to not chosen the proper operating conditions. So the effect of changing the values of the basic operating condition which are: fuel mass flow rate consumption 30 Kg/s, pressure ratio of the air compressor 16.9, inlet air temperature 22^{o}C and mass flow rate fraction of the low pressure steam 0.3 on the performance of the combined plant are investigated in turn (i.e. changing one parameter and keeping the other three parameters constant).

2.1. EFFECT OF CHANGING THE FUEL MASS FLOW RATE CONSUMPTION

As the fuel mass flow rate consumption of the two gas turbines increases from 18.46 Kg/s to 33.66 Kg/s, consequently the maximum gas temperature inlet to the gas turbines increases significantly from 919^{o}C to 1319^{o}C respectively. That leads to a significantly increase of the gas turbine power output and a slight increase of the steam turbine power output. As a result, the summation of the gas and steam turbines power output increases from 336.9 MW to 650.1 MW as shown in Fig.2a. In other words, as the maximum gas temperature increases from 919^{o}C to 1319^{o}C the power output of the combined plant increases by 93%. Consequently, the thermal efficiencies of the gas turbine and steam turbine increase gradually and the overall efficiency of the combined plant increases from 37% to 39.2% (i.e. increases by 6%) as shown in Fig.2b. Also from Fig.2c, the dryness fraction of the exhaust steam is found to be increased from 0.86 to 0.95 and unfortunately the exhaust (chimney) gas temperature increases from 93.4^{o}C (not recommended because it is less than 100^{o}C) to 278.4^{o}C which leads to extra loss of heat due to a bad design of the heat recovery steam generator. Finally, the specific power output (=total power output/total fuel consumption) is found to be increased slightly from 18.3 MW/Kg/s to 19.3 MW/Kg/s as shown in Fig.2d.

2.2. EFFECT OF CHANGING THE INLET AIR TEMPERATURE

As the inlet air temperature decreases from 40°C to -10°C, the inlet gas temperature to the gas turbine decreases significantly from 1265°C to 1154°C, but the power output of the gas turbine increases from 380.75 MW to 411.64 MW due to the increase of the inlet air density. While, for the steam turbine the power output decreases from 180.089 MW to 169.898 MW, that is due to the reduction of the gas temperature exits from the gas turbine and consequently to the reduction of heat transfer to the steam. Accordingly, the power output of the combined plant increases from 560.839 MW to 581.538 MW as shown in Fig.3a (i.e. the net power increases by 3.69%). Similarly, it is found that the steam turbine efficiency decreases but gas turbine efficiency increases slightly. Therefore, the overall combined plant efficiency increases slightly from 38% to 39.3% as shown from Fig.3b (i.e. the overall efficiency increases by 3.42%). As a result, both of the exhaust gas temperature and exhaust steam dryness fraction decreases to be 200.93°C and 0.915 respectively as shown from Fig.3c. The specific power output of the combined plant increases gradually from 18.695 MW/Kg/s to 19.108 MW/Kg/s as the inlet air temperature decreases from 40°C to 3°C, then it increases significantly up to 20.286 MW/Kg/s as the inlet air temperature further decreases down to -10°C as shown in Fig.3d. Absorption chillers could be used to reduce the inlet air temperature [12].

2.3. EFFECT OF CHANGING THE COMPRESSOR PRESSURE RATIO

As the pressure ratio of the air compressor increases from 8 to 20 (which within the practical range) , the compressed air temperature increases and consequently that leads to an increase of the gas temperature inlet to the gas turbine from 1089°C to 1251°C after the combustion process. So, the power output of the gas turbine increases but it decreases for the steam turbine. The summation of the two powers leads to an increase of the combined plant from 513.4 MW to 577 MW (i.e. an increase by 12.4%) as shown in Fig.4a. The efficiency of the gas turbine cycle increases significantly while the efficiency of the steam turbine cycle decreases slightly. So, the overall efficiency of the combined plant increases from 35% to 39% (i.e. increases by 11.42%) as shown in Fig.3b. Both of the exhaust gas temperature and steam dryness fraction decreases and exits at 224.6°C and 0.925 respectively as shown in Fig.3c. The specific power output is found to be increases significantly from 17.1 MW/Kg/s to 19.2 MW/Kg/s as shown in Fig.3d. So, re-design of the air compressor may be required.

2.4. EFFECT OF CHANGING THE MASS FLOW RATE FRACTION OF THE LOW PRESSURE STEAM

The dual pressure heat recovery steam generator (high and low pressures steam) is applied for the combined plant case study. As the mass flow rate fraction of the low pressure steam (= mass flow rate of steam at low pressure/total mass flow rate of steam) decreases from 0.95 to 0.05, that will not affect the gas turbine performance but increase the power output and efficiency of the steam turbine cycle significantly as shown in Fig.4a. Also, the overall efficiency of the combined plant increases from 35.377% to 39.4% (i.e. increases by 11.37%) and the specific power output increases from 17.438 MW/Kg/s to 19.42 MW/Kg/s as shown in Fig.4d accompanied with a reduction of steam dryness fraction down to low value of 0.885. So, re-design for the dual steam generator and turbines may be required.

2.5. EFFECT OF ADDING SUPPLEMENTARY FIRING SYSTEM

For the combined plant case study the fuel consumption flow rate in the combustion chambers of the gas turbines is 30 Kg/s. Extra amount of the fuel 3.66 Kg/s is added to the combustion chambers of the gas turbines and other time to the heat recovery steam generator such that the total fuel consumption flow rate for both cases becomes the same of 33.66 Kg/s (at which the thermal performance is high). It can be noticed that, as the extra fuel is burnet in the supplementary firing system the power output of the steam cycle increases slightly while the power of the gas turbine remains as it is and the overall power output of the plant increases from 570.669 MW to 587.962 MW. While burning the extra fuel in the combustion chambers of the gas turbines instead of supplementary system leads to a significant increase of the power output of gas turbine cycles as well as of the combined plant from 394.962 MW and 570.669 MW to be 465.288 MW and 650.113 MW respectively. Adding extra fuel in the combustion chambers produces overall efficiency of 39.18% greater than that in supplementary system which produces overall efficiency of 35.4%. So, it is recommended to burn the extra fuel in the combustion chambers of the gas turbines rather than in the supplementary system if higher power, higher overall efficiency and lower exhaust gas temperature are required as shown from Fig.5. But, materials of ducts and turbines blades with higher specifications in order to withstand the higher thermal stress will be needed and will be much costly.

2.6. CORRELATIONS

Correlations have been done in order to correlate the net power output and overall efficiency of the combined plant with the investigated operating parameters which are: the total fuel mass flow rate, inlet air temperature, pressure ratio, and mass flow rate fraction of the low pressure steam using statistical package social sciences (S.P.S.S.) software in order to analyze the data using multiple liner regression models. The net power output of the combined plant correlation is expressed as:

$$\boldsymbol{Power}_{Combined} = -3.712 + 20.37\dot{m}_{fuel} + 5.678R_P - 0.417T_{air} - 65.072\frac{\dot{m}_{steam\ LP}}{\dot{m}_{total\ Steam}}$$

Error rate equation = 3.49925%

Also, the overall efficiency of the combined plant correlation is expressed as:

$$\boldsymbol{\eta}_{Combined} = 37.569 + 0.133\dot{m}_{fuel} + 0.364R_P - 0.027T_{air} - 4.393\frac{\dot{m}_{steam\ LP}}{\dot{m}_{total\ Steam}}$$

Error rate equation =0.19624%

Where:

$Power)_{Combined} =$ $Net\ output\ power\ of\ the\ combined\ plant$ MW

$\eta_{Combined} =$ $Overall\ efficiency\ of\ the\ combined\ plant$ %

$\dot{m}_{fuel}$ = $Fuel\ mass\ flow\ rate\ consumption\ in\ combustion\ chamber$ kg/s

$R_P = Compressor\ pressure\ ratio - T_{air} = Inlet\ air\ temperature$ K

$\frac{\dot{m}_{steam\ LP}}{\dot{m}_{total\ Steam}} =$ $mass\ flow\ rate\ fraction\ of\ low\ pressure\ steam$ –

$= \frac{mass\ flow\ rate\ of\ steam\ at\ low\ pressure}{total\ mass\ flow\ rate\ of\ steam}$ -

3. CONCLUSIONS

1- The study is an attempt to increase the net power output and overall efficiency of the combined plant by increasing the maximum gas temperature and pressure ratio but reducing the inlet air temperature and mass flow rate fraction of the low pressure steam. The previous parameters are correlated in good obtainable correlations as follows:

$$\boldsymbol{Power}_{Combined} = -3.712 + 20.37\dot{m}_{fuel} + 5.678R_P - 0.417T_{air} - 65.072\frac{\dot{m}_{steam\ LP}}{\dot{m}_{total\ Steam}}$$

$$\eta_{Combined} = 37.569 + 0.133\dot{m}_{fuel} + 0.364R_P - 0.027T_{air} - 4.393\frac{\dot{m}_{steam\ LP}}{\dot{m}_{total\ Steam}}$$

2- Increasing the basic fuel consumption rate from 30 Kg/s to 33.66 Kg/s (i.e. increasing the maximum inlet gas temperature from 1219^{o}C to 1319^{o}C) this will lead to an increase of the power output and overall efficiency by 13.92% and 1.53% respectively.

3- Decreasing the basic inlet air temperature from 40^{o}C to -10^{o}C leads to an increase of the power output and overall efficiency by 3.69% and 3.42% respectively.

4- Increasing the basic air compressor pressure ratio from 16.9 to 20 leads to an increase of the power output and overall efficiency by 1.11% and 1.06% respectively.

5- Decreasing the basic mass flow rate fraction of the low pressure steam from 0.3 to 0.05 leads to an increase of the power output and overall efficiency by 2.1%and 2.1% respectively.

6- The optimum values from the above operating parameters are chosen to operate together. The corresponding obtainable power output is found to be increased up to 713.5 MW and the overall efficiency increased up to 41.4%. In other words the net power output increases by 25.03% and the overall efficiency increases by 7.28%. To achieve that, re-design of some elements of the combined plant may be required.

7- Burning extra fuel in the basic combustion chamber produces significantly higher power output and higher overall efficiency rather than burning the extra fuel in the supplementary firing system. But costly materials for ducts and turbines blades with higher technical specification must be considered.

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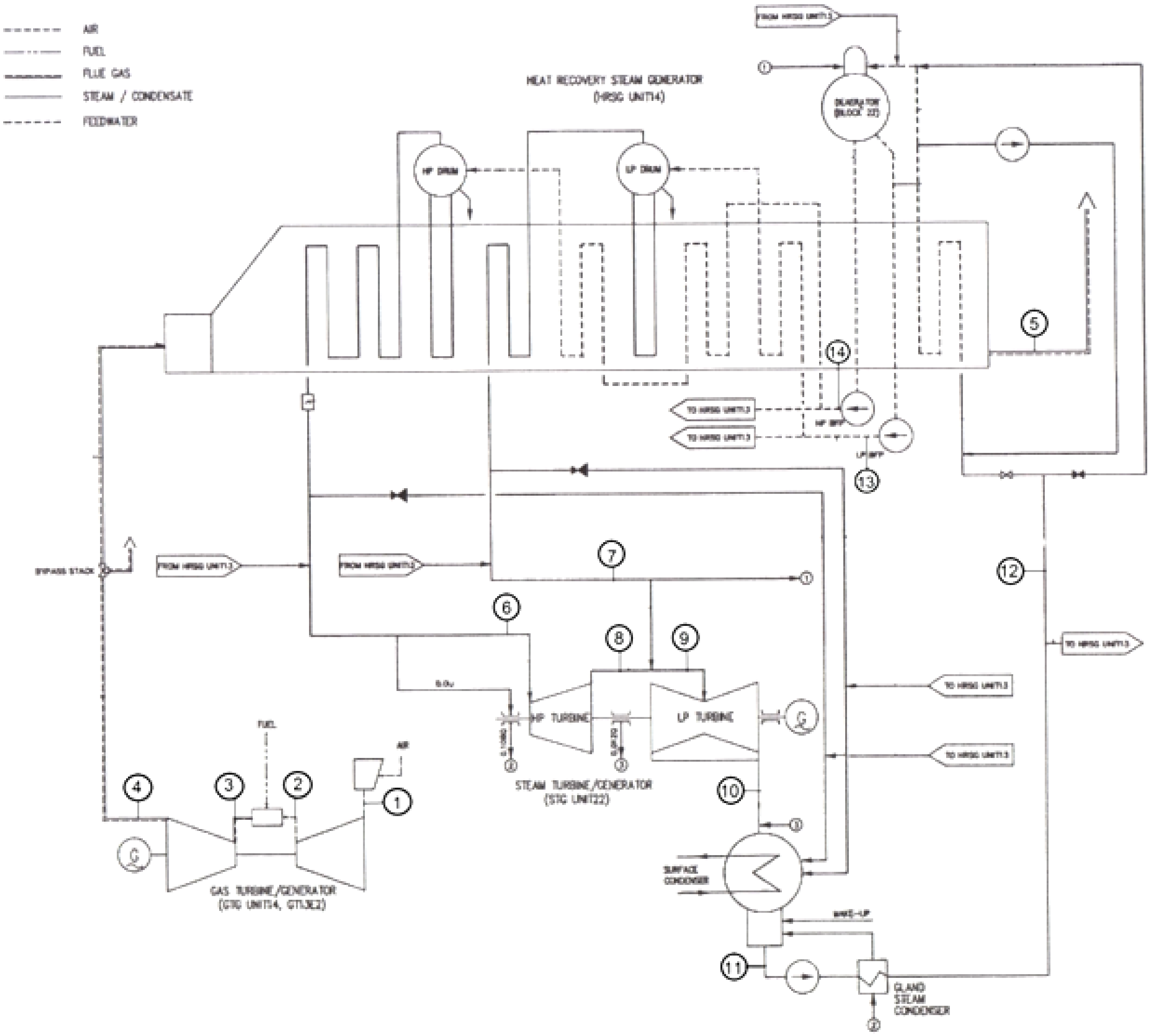
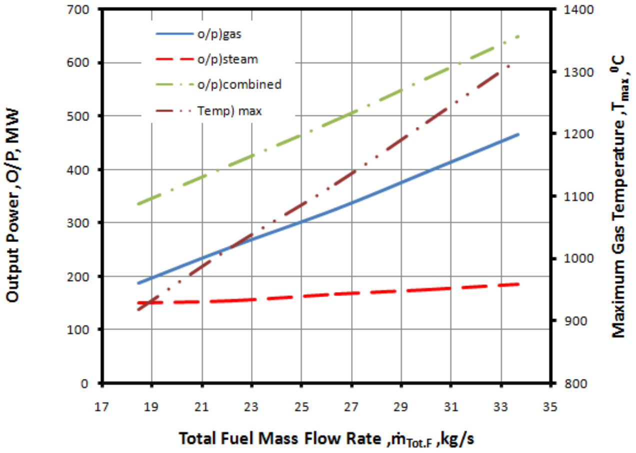
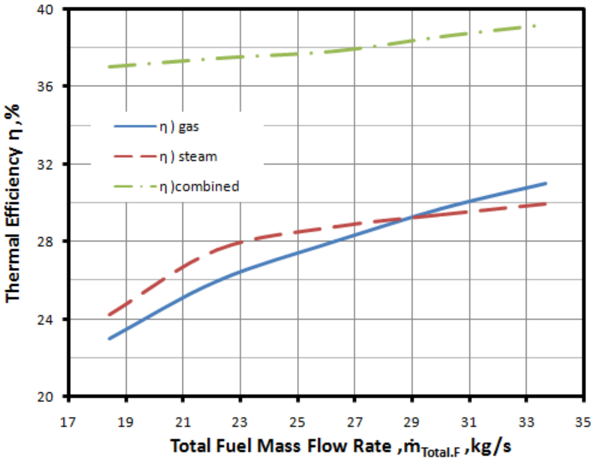
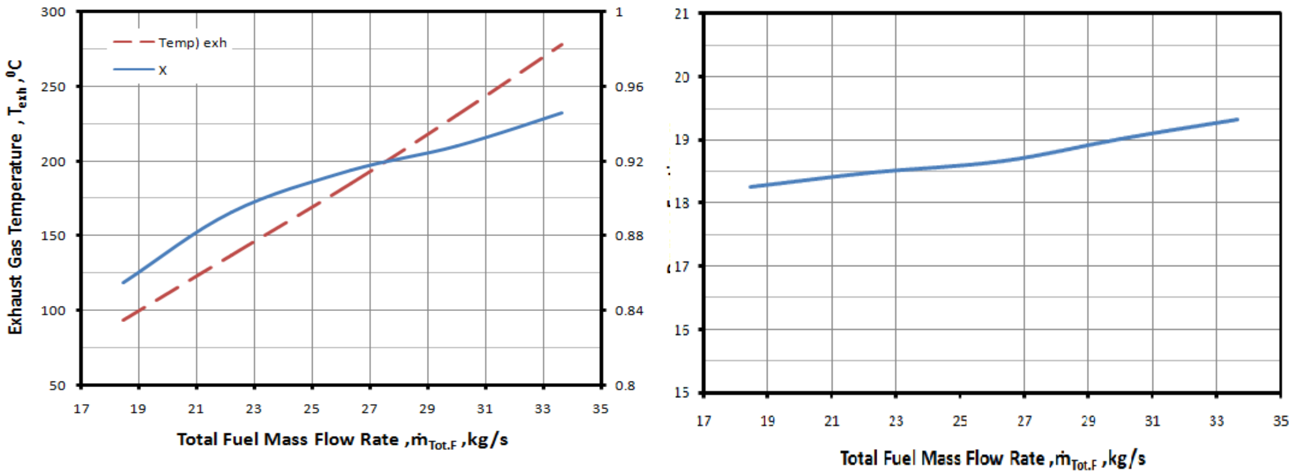


Fig.1 The Flow Diagram of The Combined Power Plant



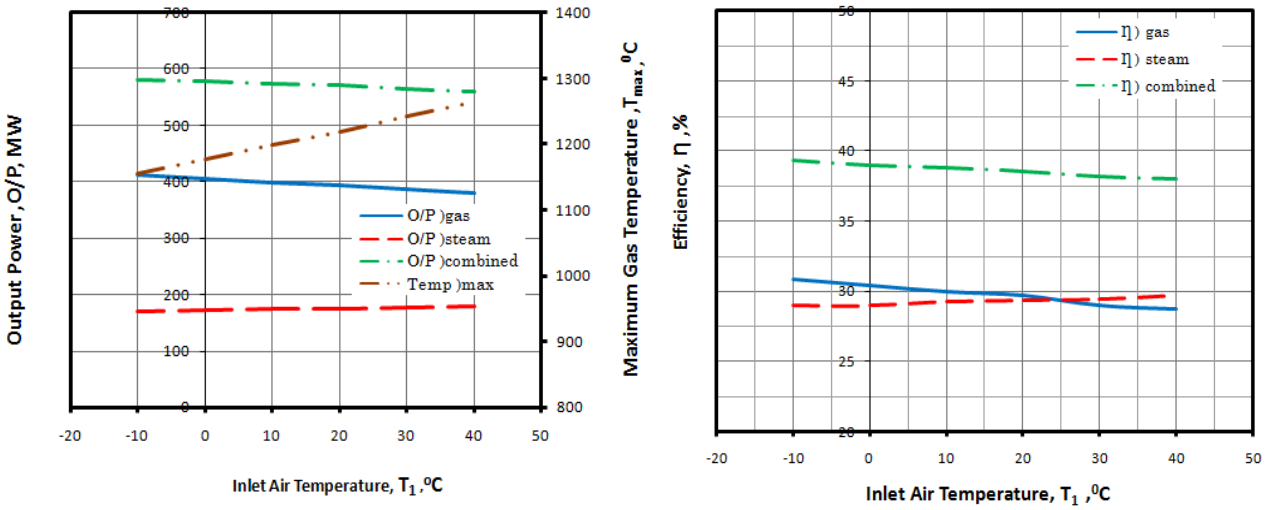


(a) (b)



(C) (d)

Fig.2 Effect of changing the fuel mass flowrate consumption on the performance of the combined plant.
(R_P=16.9, T_{air}=293K, $\frac{\dot m_{L.P\,Steam}}{\dot m_{Total\ .Steam}} = 30\%$)



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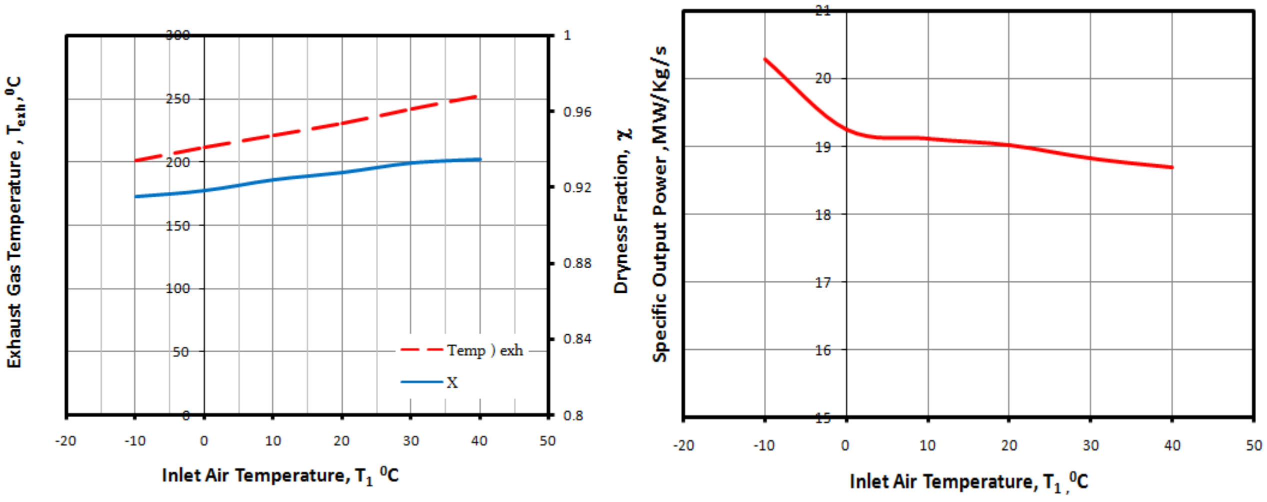
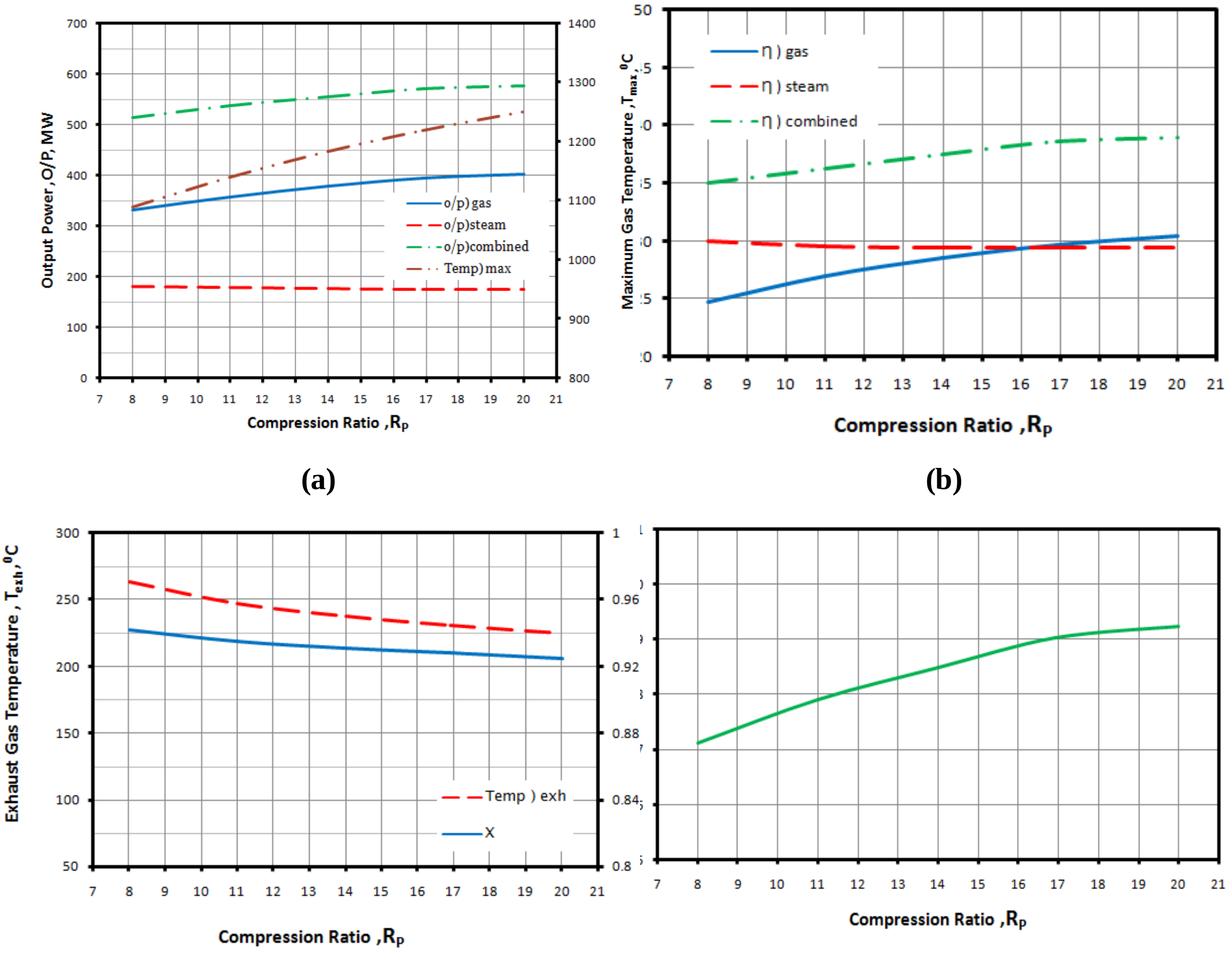


(C) (d)

Fig.3 Effect of changing the inlet air temperature on the performance of the combined plant.

$(\dot{m}_{fuel} = 30\text{Kg/s}, \text{R}_\text{P}\text{=16.9}, \frac{\dot{m}_{L.P\,Steam}}{\dot{m}_{\text{Total .Steam}}} = 30\%)$

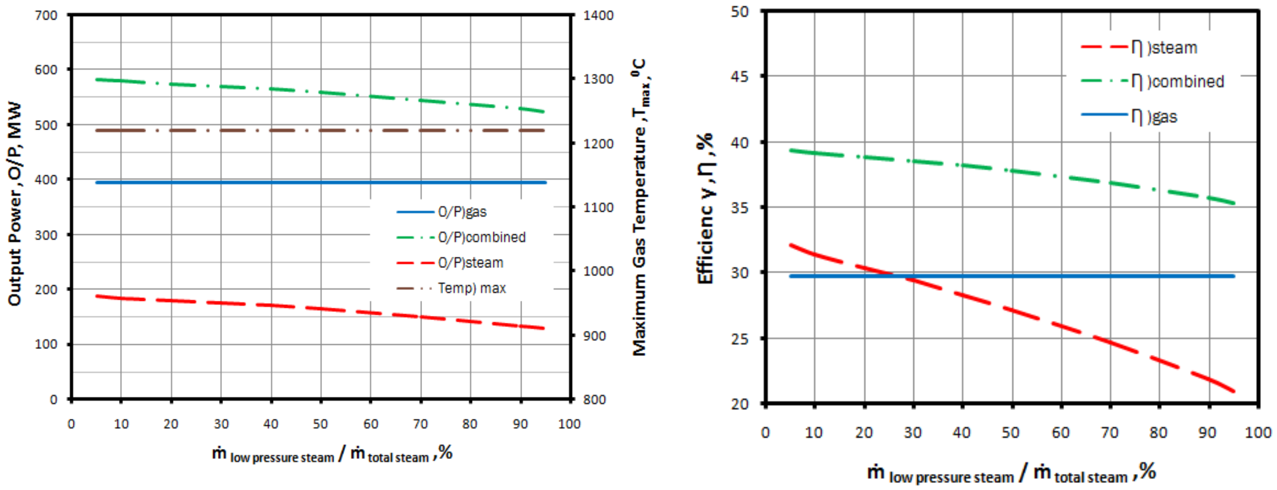


(a) **(b)**

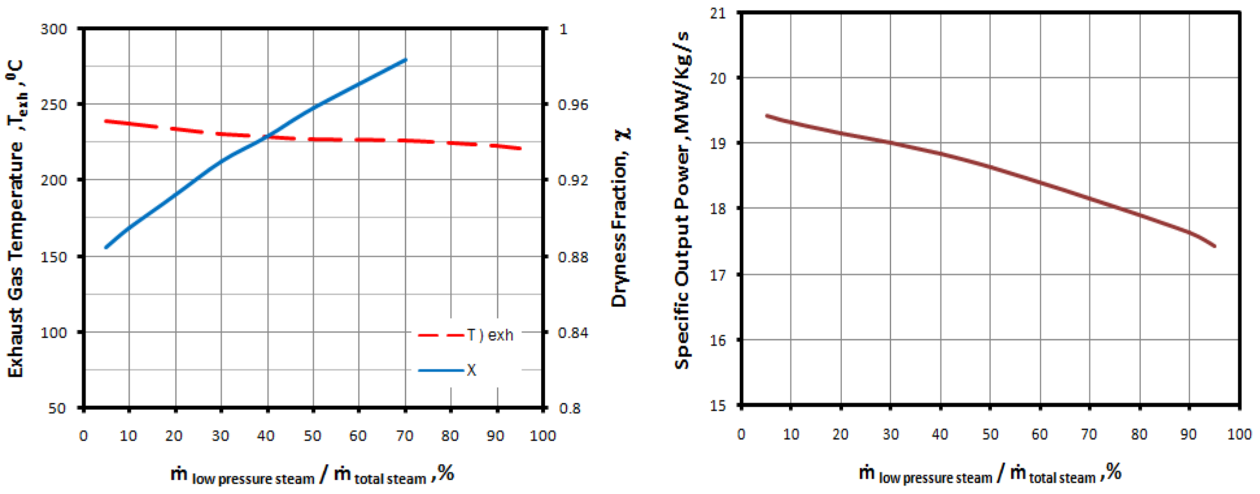
(c) **(d)**

Fig.4 Effect of changing the compressor pressure ratio on the performance of the combined plant.

$(\dot{m}_{fuel} = 30\text{Kg/s}, \text{T}_{\text{air}}\text{=293K}, \frac{\dot{m}_{L.P\,Steam}}{\dot{m}_{\text{Total .Steam}}} = 30\%)$



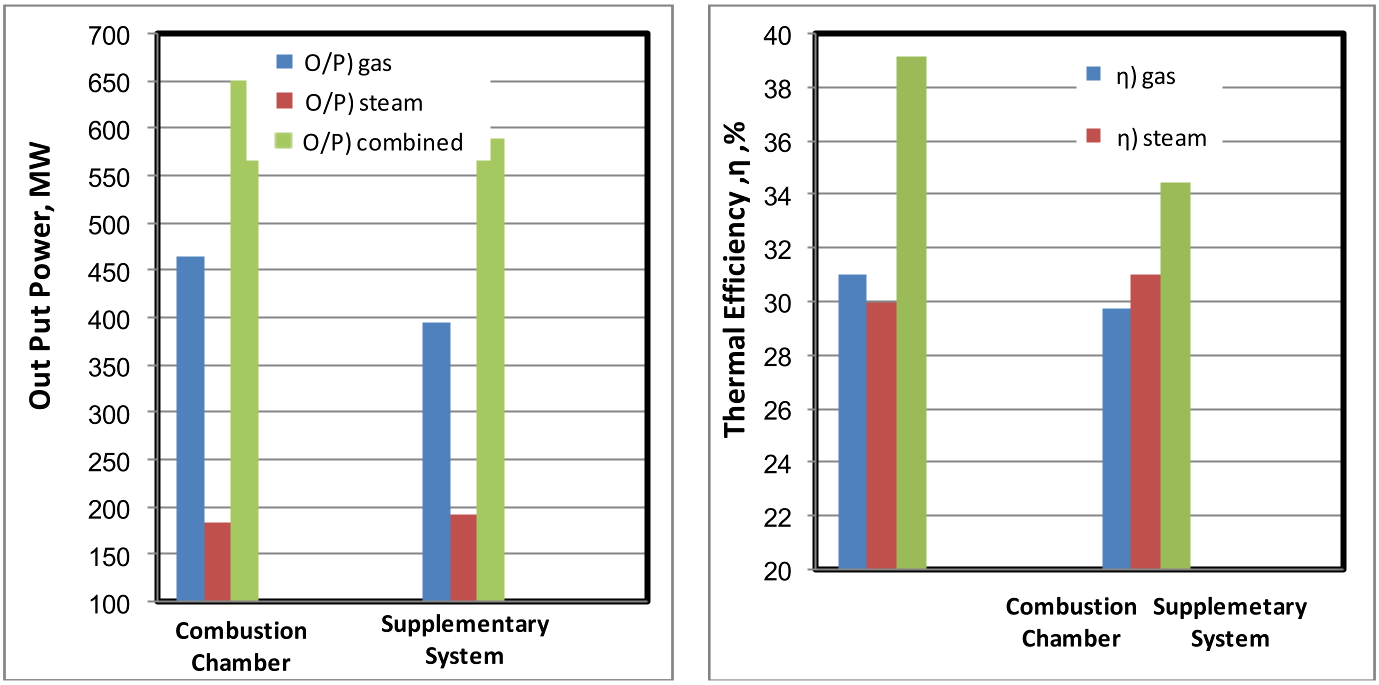
(a) **(b)**



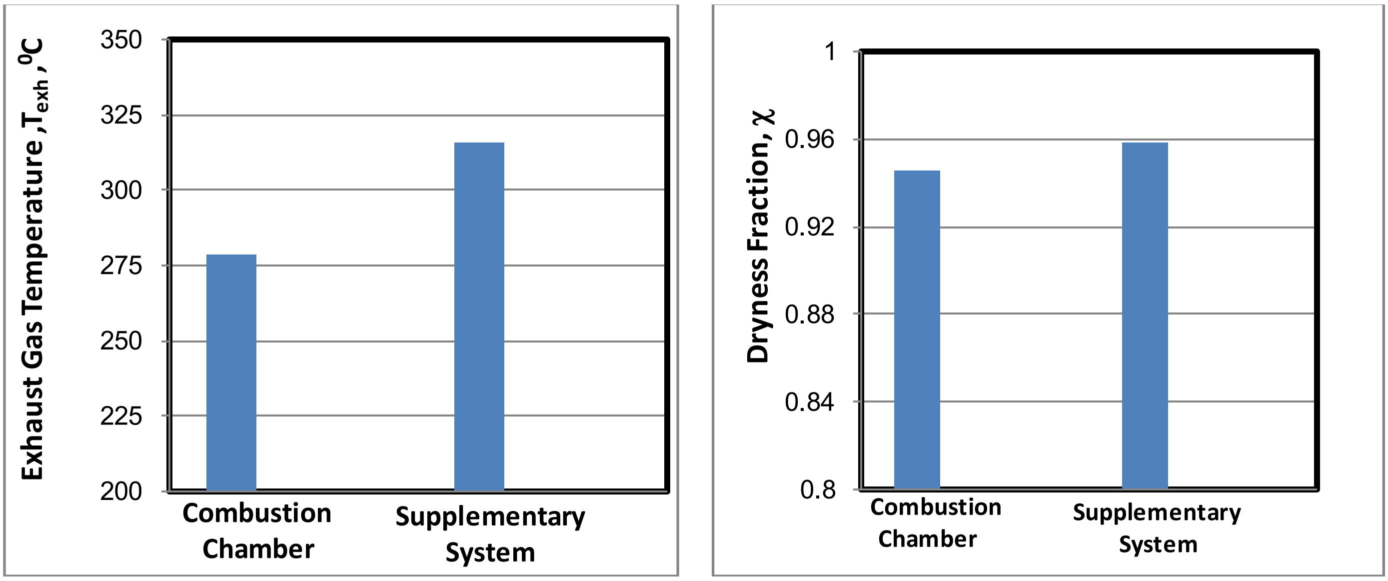
(C) (d)

Fig.5 Effect of changing the mass flowrate fraction of the low pressure steam on the performance of the combined plant.

(R_P=16.9, T_{air}=293K, $\dot{m}_{fuel} = 30Kg/s$)



(a) (b)



(c) (d)

Fig.6 Comparison of Burning Extra Fuel in Combustion Chamber or Supplementary System.