DUAL-PRESSURE HEAT RECOVERY BOILER OF COMBINED GAS/STEAM POWER PLANTS

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الملخص

وُجِّهَ هذا البحث نحو الدراسةِ النظريةِ لأداء محطات التوربينات الغازية والبخارية المزدوجة التي تشمل غلاية استعادة الحرارةٍ الثنائية الضغط حيث الوقود المستخدم عبارة عن الغاز الطبيعي الذي يتكون حجميا من 90% ميثان و 10% إيثان. حيث يهتم البحث بدراسة تأثير معاملات غلاية استعادة الحرارة الثنائية الضغط وهى عبارة عن ضغط ودرجة حرارة كلا من البخار ذو الضغط العالي والمنخفض والنسبة مابين كتلة البخار ذو الضغط المنخفض إلى كتلة البخار ذات الضغط العالي على أداء الدورة المزدوجة. وقد أظهرت النتائج أن كفاءة الدورة المزدوجة والشغل الناتج يتأثران بدرجه كبيره بالضغط العالي والضغط المنخفض في غلاية استعادة الحرارة الثنائية الضغط حيث يزيدان بزيادة قيمة الضغط العالي وبنقصان قيمة الضغط المنخفض.وأوضحت النتائج أيضا بأن درجة حرارة البخار ذو الضغط العالي الخارج من الغلاية له تأثير ملحوظ على الشغل وكفاءة الدورة المزدوجة بينما درجة حرارة البخار ذو الضغط المنخفض لها تأثير مهمل على كفاءة الدورة المزدوجة وبذلك يمكن الاستغناء عن محمص البخار ذو الضغط المنخفض في غلاية استعادة الحرارة الثنائية الضغط. كما بينت النتائج بأن النسبة مابين كتلة البخار ذات الضغط المنخفض إلى كتلة البخار ذو الضغط العالي المثالية التي تعطى أقصى شغل وكفاءة للدورة المزدوجة هي 0.2.

ABSTRACT

The present work has been directed towards the theoretical study of the combined gas/steam turbine power plant incorporating dual-pressure heat recovery boiler. The considered fuel was a natural gas having a composition of 90% methane and 10% ethane by volume. The effects of the parameters of dual-pressure heat recovery boiler, namely the pressures of high-pressure (HP) and low pressure (LP) drums, temperatures of high-pressure and low-pressure steam, and the mass ratio of low-pressure steam to high-pressure steam (m_{LH}), on the performance of the combined cycle have been considered in the present paper. The results revealed that the net specific power output and the overall efficiency of the combined plant are significantly influenced by the pressures of HP and LP drums of the dual pressure heat recovery boiler. They increased with the increase of the pressure of HP drum and with the decrease of the pressure of LP drum. The temperature of the generated HP steam has a considerable effect on the specific power and overall efficiency of combined plant while the temperature of generated LP steam has a negligible effect. The results also showed that the optimum mass ratio, m_{LH}, that gave maximum specific power and overall efficiency, was 0.2.

KEYWORDS: Combined cycle; Dual-pressure heat recovery boiler; LP and HP drums; Mass ratio; Steam cycle efficiency; Power ratio; Overall efficiency

INTRODUCTION

Recently the concept of a combined gas/steam power plant (CGSPP) has been gaining widespread acceptance, because of its higher efficiency and reduced pollution levels. The design of such combined cycle power plants is, however, much more involved because of coupling between the two power-producing cycles, the topping gas turbine cycle and the bottoming steam turbine cycle, brought about by the heat recovery boiler (HRB).

Many publications were concerned with the thermodynamic analysis and the optimization of the combined cycle power plants, such as [1-7]. Mikhael and Morad [1] analyzed three different configurations for the CGSPP with coal gasification system. The cycle configurations considered were combined cycle with supercharged boiler, with heat recovery boiler, with and without supplementary firing. They concluded that the supercharged boiler combined plant was the most promising from the viewpoint of the capital cost and showed the sharp reduction in its overall thermal efficiency, if the load control was shared by the GT- and ST-plants. Larson and Williams [8] studied the effect of steam injection on the performance of CGSPP. They concluded that, without steam injection the thermal efficiency varied between 40.1 and 45.8 for the pressure ratios considered, while with steam injection, the thermal efficiency improved significantly and continuously until a heat recovery limitation was reached. Rice [9] analyzed a combined reheat gas/steam turbine cycle. He concluded that the combined cycle incorporating the reheat gas turbine offered significant cycle improvements for equal firing temperatures. Akiba and Thani [4] studied the performance of combination of supercharged boiler-gas turbine cycle and heat recovery boiler from a thermodynamic point of view. Two designs of this cycle were adopted and the influences of various operating parameters, such as compressor pressure ratio, inlet gas temperature of gas turbine, percentage excess air, ambient temperature, and the number of feed water heaters, were studied. A performance comparison between the adopted cycles and a conventional heat recovery boiler cycle was made. The results showed that there was an improvement in overall efficiency of about 8.5-9.5 percent with the first design of the adopted cycles over the conventional heat recovery boiler cycle. Seyedan et al [10] developed a procedure for optimum design of waste heat recovery boiler of a combined cycle power plant. This method enables the optimization of waste heat recovery boiler independent of the rest of the system and the design thus obtained could directly be employed in an existing plant. Wu and Louis [11] presented a comparative study of the influence of different means of cooling on the thermodynamic efficiency and specific power of combined gas and steam cycle. In this study, the exhaust of the gases turbine were used as the heat source to a steam cycle using single reheat with a specified temperature difference at the pinch point. The sensitivity of the overall efficiency to each key input parameter was reported. Bolland [12] considered several alternative arrangements of combined gas/steam combined cycle to improve the overall efficiency. The effect of supplementary firing was also considered for some cases. The different alternatives were compared with respect to efficiency, required heat transfer area, and stack temperature. A full exergy analysis was given to explain the performance differences for the cycle alternatives. Jericha and Holler [13] used hydrogen as the fuel for the combined gas/steam power plant. A novel peak power plant was presented with internal combustion of hydrogen with oxygen. Thus a very high efficiency of reuse of a most valuable fuel generated fuel generated by electrolysis from surplus hydraulic sources during periods of low power demand or transported from solar sites was achieved

In a combined cycle power plant the air compressor, the gas and steam turbines, various pumps, valves, etc, are standard equipments, which are available in various standard sizes. Since the HRB is the equipment that couples the two power- producing cycles of a combined cycle power plant, therefore, a HRB is the only key component that is specifically designed and built for every combined power plant. Any change in the HRB operating parameters influences the power output of both the steam cycle and gas turbine cycle. While carrying out the search for optimal design of a HRB, it is therefore essential to estimate the power output of a CGSPP for every potential design and choose only those design that give the maximum output power and overall efficiency. Therefore, the present paper has been directed to study the effects of the parameters of dual-pressure HRB, namely, the high-pressure and low-pressure steam pressures and temperatures and mass ratio of low-pressure to high-pressure steam, on the performance of the CGSPP.

DESCRIPTION OF THE CONSIDERED COMBINED CYCLE

The considered CGSPP with dual-pressure heat recovery boiler is shown in Figure (1). The compressor supplies pressurized air to the combustion chamber. All combustion takes place in the combustion chamber and the fuel considered is a natural gas.

The product gas from the combustion chamber is expanded as it flows through the gas turbine. The gas turbine drives both the compressor and the generator. The gas from the gas turbine exhausts into a dual-pressure heat recovery boiler to generate steam. In turn, the steam is used to run a steam turbine. The dual-pressure heat recovery boiler consists of different sections from the exhaust gas inlet are; the high-pressure superheater (HPSH), high-pressure evaporator (HPEV), high-pressure economizer (HPEC), low-pressure superheater (LPSH), low-pressure evaporator (LPEV), low-pressure economizer, and stack gas economizer (SGEC).

Since the overall efficiency of the combined cycle power plant determined mainly by the parameters that fix the efficiency of the GT cycle than those of the ST cycle. The important parameters of ST cycle are pressures of the HP- and LP-drums, the temperatures of the HP and LP steams generated from the HRB, and the mass ratio of LP steam to HP steam ($m_{LH} = m_{LPS}/m_{HPS}$). The condenser pressure depends strongly on the temperature of the available cooling water, and it is approximately constant at different loads. In order to get as close as possible to the stack gas temperature, the parameters of dual-pressure boiler must be selected carefully. The first question to be considered is what optimum pressures should be selected in the dual-pressure boiler. The pressure of HP drum dictates the temperature at which evaporation sets in, i.e., the pinch point, thereby also determining the HP steam mass flow rate which can be generated. Finally, the extending of exhaust gas cooling is also determined by the selected pressure of LP drum. A diagram showing T and Q interdependencies illustrates this point. Figure (2) is the T-Q diagram which plots temperature profiles versus Q to show the heat flow from the flue gas to the water/steam in the dual pressure heat recovery boiler for the investigated plant. The temperature difference at pinch point for HP and LP drums are also shown in this figure.

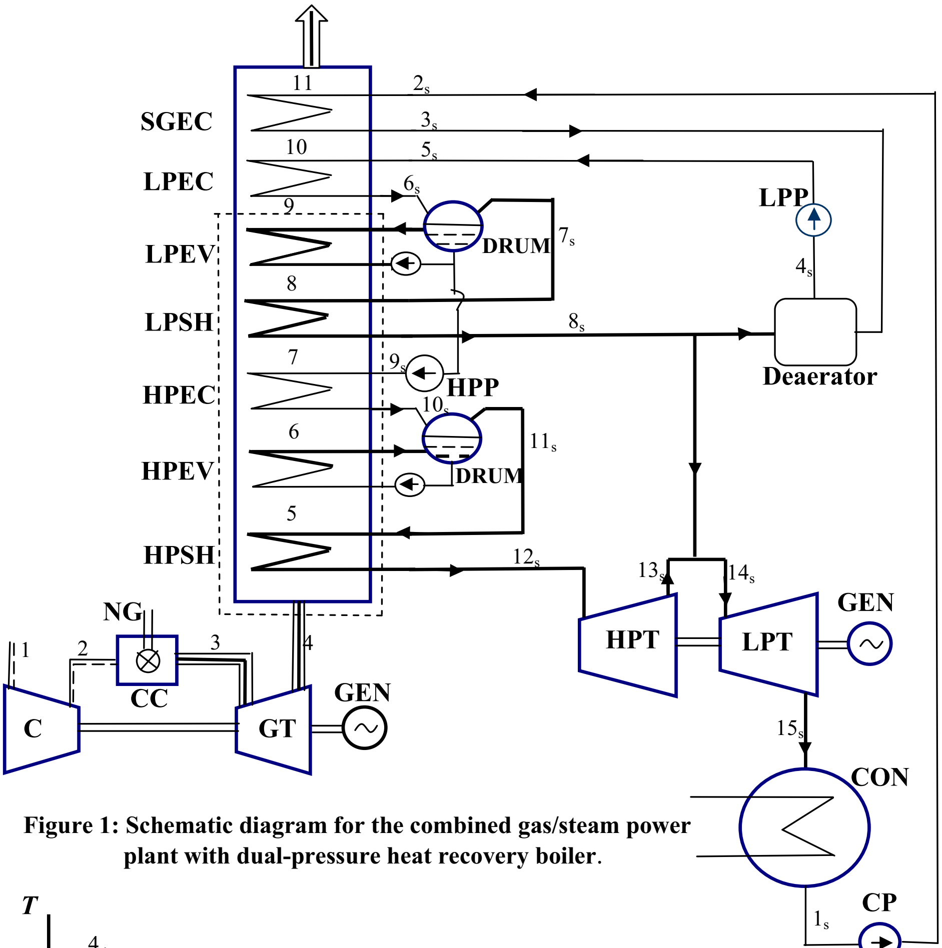

Figure 1: Schematic diagram for the combined gas/steam power plant with dual-pressure heat recovery boiler.

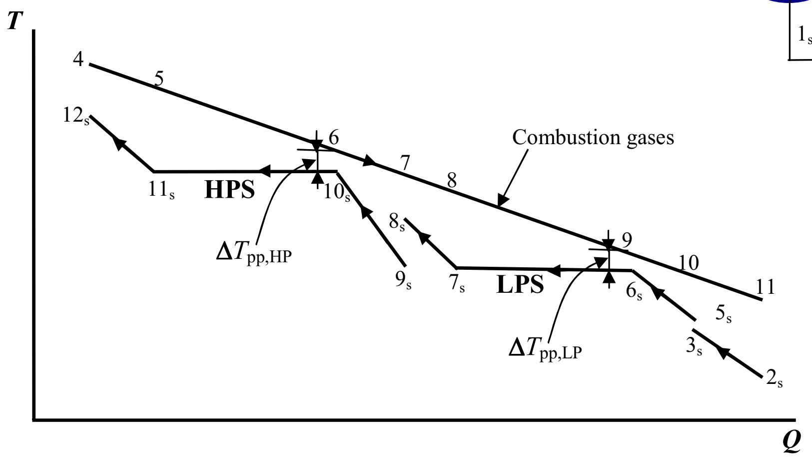

Figure 2: *T-Q* diagram for dual-pressure heat recovery boiler

ANALYSIS

In order to evaluate the performance of a CGSPP, thermal analysis of each component must be carried out. In this analysis, the change of specific heat of combustion gases and air with the change of temperature of the working media and composition were considered, the change of environmental or technological factors, such as ambient air pressure and temperature, efficiency of each component, etc, were not considered, the heat loss and pressure drops at the air intake, combustion chamber and exhaust stack, and also the steam pressure losses were not considered, and the influence of the feed-water pumps work was considered. All calculations are based on 1 kmol of natural gas of composition of 90% methane and 10% ethane by volume. With natural gas fuel, the temperature of stack gas leaving the HRB may be below 100^{o}C which is permissible for the natural gas fuel with low sulfur content.

For a defined value of compressor pressure ratio (π = 12) and gas turbine inlet temperature (T_3 =1100^{o}C), the excess air factor,λ, (actual air/theoretical air) for the combustion process is determined iteratively from the combustion equation and energy balance equation for the combustion chamber;

- Combustion equation:

$$0.9CH_4 + 0.1C_2H_6 + \lambda.n_{O_2}(1+3.76N_2) \rightarrow 1.1CO_2 + 2.1H_2O + (1-\lambda).n_{O_2}O_2 + 3.76\lambda.n_{O_2}N_2 \quad (1)$$

where n_{O_2} is the theoretical O_2 required to burn 1 kmol of natural gas ($n_{O_2} = 1.1 + 2.1/2 = 2.15$ kmol/kmol$_{fuel}$)

- Energy balance equation:

$$X_{air}\overline{C}_{P,air}T_2 + Hu = X_g\overline{C}_{P,gas}T_3 \quad (2)$$

where T_2 is the compressor exit temperature, T_3 is the gas turbine inlet temperature, as shown in Figure (1), X_{air} is the actual air required per kmol of fuel ($X_{air} = 4.76\lambda.n_{O_2}$ kmol/kmol$_{fuel}$), X_g is the amount of combustion gases per kmol fuel ($X_g = 1.1 + 2,1 + (1-\lambda)n_{O_2} + 3.76\lambda.n_{O_2}$ kmol/kmol$_{fuel}$), $\overline{C}_{P,air}$ and $\overline{C}_{P,gas}$ are the molal specific heat of air and product gases, respectively, and Hu is the molal calorific value of the natural gas.

- Since the thermodynamic properties of each point in the Brayton cycle are known, the net specific power of gas turbine cycle can be calculated;

$$W_{n,g} = \{X_g\overline{C}_{P,g}(T_3 - T_4)\eta_m - X_{air}\overline{C}_{P,air}(T_2 - T_2)/\eta_m\}\eta_G \quad (3)$$

- The mass of HP steam can be calculated from the energy balance for the dotted section of HRB shown in Figure (1);

$$m_{HP} = \frac{X_g\overline{C}_{P,g}(T_4 - T_9)}{h_{12_s} - h_{9_s} + m_{LH}(h_{8_s} - h_{6_s})} \quad (4)$$

- The steam cycle efficiency is calculated as;

$$\eta_{ST} = \frac{W_{n,s}}{X_g\overline{C}_{P,g}(T_4 - T_{11})} \quad (5)$$

where T_{11} is the stack gas temperature.

- The overall efficiency of the CGSPP is given by;

$$\eta_o = \frac{W_{n,comb}}{Hu} \tag{6}$$

where

$$W_{n,comb} = W_{n,g} + W_{n,s} \tag{7}$$

A computer code was developed to evaluate gas turbine cycle, the heat recovery boiler, and steam turbine cycle. Different subprograms concerned with thermodynamic properties of air, gases and the water are used to estimate the generated HP steam, net power, ST cycle efficiency and overall efficiency of combined power plant. The required input parameters, such as temperature at turbine inlet, compressor pressure ratio, efficiency of the turbomachine, etc, and range of operating parameters are given in Table (1).

Table 1: Inlet conditions and range of operating parameters

Natural gas composition	90% CH_4 and 10% C_2H_6 on mole basis
Ambient air conditions	30^{o}C, 1 bar, 60% relative humidity
Compressor pressure ratio	12
GT inlet temperature	1100^{o}C
Compressor isentropic efficiency	87%
GT isentropic efficiency	87%
Pressure of HPS	40 – 120 bar
Pressure of LPS	4 – 12 bar
Deaerator pressure	2 bar
Condenser pressure	0.06 bar
Temperature of HPS	425 – 475^{o}C
Temperature of LPS	200 – 250^{o}C
Temperature difference at LP pinch point	15^{o}C
Temperature difference at HP pinch point	is calculated and must be greater than 15^{o}C
LPS to HPS mass ratio	0.15 – 0.4
ST isentropic efficiency	87%
Pump polytropic efficiency	75%
Mechanical efficiency	97%
Generator efficiency	98%

DISCUSSION OF RESULTS

To explain the effects of parameters of dual-pressure boiler on the performance of CGSPP, the HP-drum steam pressure and temperature were changed from 40 to 120 bar and 425 to 475^{o}C, respectively. The LP-drum steam pressure and temperature were changed from 4 to 12 bar and 200 to 250^{o}C, respectively. The effect of the mass ratio, m_{LH}, on the performance of the CGSPP was also studied. The GT-parameters were fixed with changing the parameters of dual pressure heat recovery boiler. The temperature difference at LP pinch point was kept constant for all cases.

Figure (3) represents the ST-plant efficiency as a function of the pressure of HP drum at various temperatures of high pressure steam (HPS). The efficiency of ST plant increases with the increase of pressure of HP drum and temperature of HPS.

Figure (4) shows the overall efficiency of CGSPP versus the pressure of HP-drum at different temperatures of HPS. The overall efficiency of combined cycle increases also with the increase of HP-drum and temperature of HPS.

Figure (5) displays the computed results of the net specific power output per kmol of natural gas dependent on the pressure of HP-drum and temperature of HPS. The net power output increases significantly with the increase of pressure of HP-drum and temperatures of HPS.

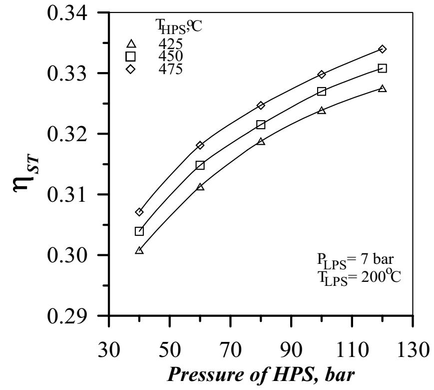

Figure 3: ST-cycle efficiency at different pressures and temperatures of HPS

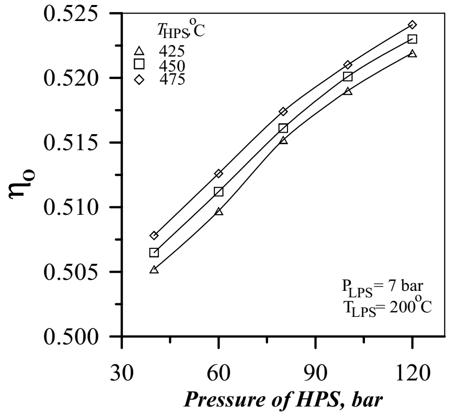

Figure 4: Overall efficiency of CGSPP at different pressures and temperatures of HPS

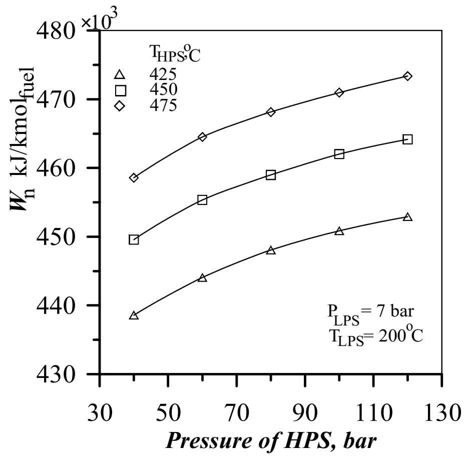

Figure 5: Net specific power of CGSPP at different pressures and temperatures of HPS

Figure (6) shows the ST-cycle efficiency versus the pressure of LP-drum at different temperatures of low-pressure steam (LPS). The ST-cycle efficiency increases with the increase of pressure of LP drum while the LPS temperature has a slight effect on the efficiency of ST plant. The stack gas temperature (T_{11}) increases and the heat supplied to steam cycle decreases with the increase of pressure of LPS. Therefore, the efficiency of ST cycle increases with the increase of pressure of LPS.

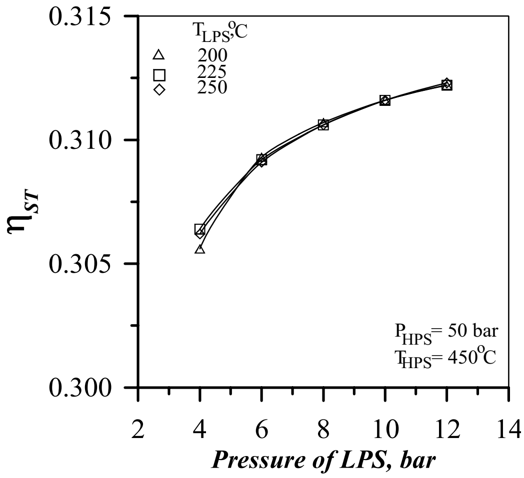

Figure 6: ST-cycle efficiency at different pressures and temperatures of LPS

Figure (7) shows the overall efficiency of the combined cycle at different pressures of LP-drum and temperatures of LPS. The overall efficiency slightly influenced with the LPS temperature and decreases continuously with the increase of pressure of LP drum.

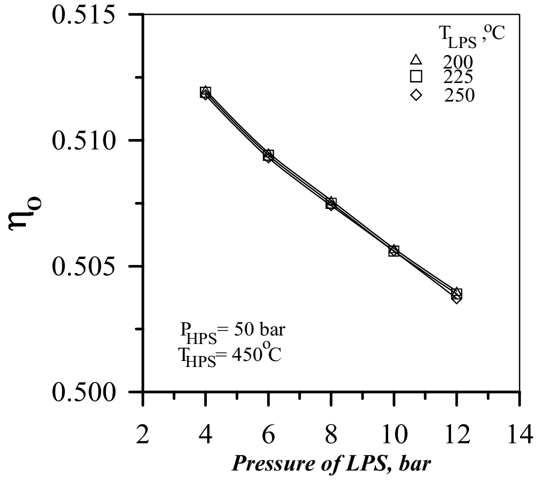

Figure 7: Overall efficiency of CGSPP at different pressures and temperatures of LPS

The trend of variation of net specific power output of CGSPP with pressure and temperature of LPS is the same as for the overall efficiency, decreases with the increase of pressure of LPS and slightly influenced by the temperature of LPS, as shown in Figures (7-8). The important conclusion from Figures (6-8) is that the superheating section for LP steam may not be incorporated in the dual-pressure HRB.

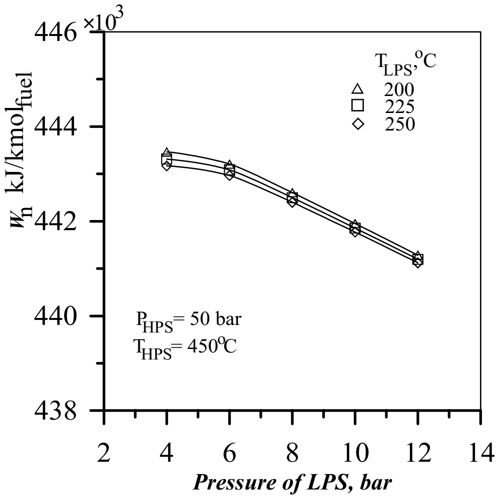

Figure 8: Net specific power of CGSPP at different pressures and temperatures of LPS

Figure (9) shows the influence of mass ratio of HPS to LPS, m_{LH}, (m_{LPS}/m_{HPS}) on the ST-cycle efficiency, overall efficiency of combined plant and on the specific power ratio (W_{ST}/W_{GT}). The ST-cycle efficiency decreases with the increase of mass ratio. The maximum overall efficiency and power ratio and hence the maximum specific power of ST cycle occur at approximately steam mass ratio of 0.2

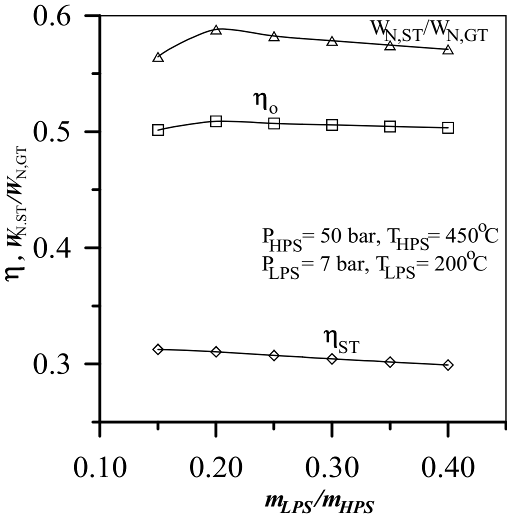

Figure 9: ST-cycle efficiency, combined cycle efficiency, and work ratio at different steam mass ratio, (m_{LPS}/m_{HPS}).

CONCLUSIONS

This paper presented a thermodynamic analysis of the combined gas/steam turbines power plant with dual-pressure heat recovery boiler without supplementary firing. The aim of the present project is to study the effects of parameters of the dual-pressure heat recovery boiler on the performance of the combined cycle. Based on the assumptions made and the results obtained, the following conclusions are drawn:

- The overall efficiency and net specific power output of the combined plant increases with the increase of pressure of HP-drum and temperature of HPS.
- The overall efficiency and net specific power output of the combined plant decreases continuously with the increase of pressure of LP drum.
- The temperature of LPS has a negligible effect on the overall efficiency and net specific power output of combined plant and, therefore, the Low-pressure superheater section may not be incorporated in the dual-pressure HRB.
- The maximum combined cycle efficiency and maximum power ratio occurs at steam mass ratio (mass of low-pressure steam to high-pressure steam) of about 0.2

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NOMENCLATURE

$\overline{C}_P$	molal specific heat at constant pressure, kJ/kmol K
h	specific enthalpy, kJ/kg
Hu	calorific value, kJ/kmol
m_{HP}	mass of high-pressure steam, kg/kmol$_{\text{fuel}}$
m_{LH}	mass ratio, m_{HPS}/m_{LPS}
P	pressure, bar
T	temperature, K
X_{air}	amount of actual air required for combustion, kmol/kmol$_{\text{fuel}}$
X_g	amount of product gas from combustion, kmol/kmol$_{\text{fuel}}$
w	specific work, kJ/kg
W	specific work, kJ/kmol$_{\text{fuel}}$

GREEK

η	efficiency
λ	excess air factor
Δ	difference
μ	mass fraction

SUBSCRIPT

comb	combined
G	generator
HP	high pressure
LP	low pressure
m	mechanical
n	net work
o	overall
s	steam

ABBREVIATIONS

C	compressor
CC	combustion chamber
CGSPP	combined gas/steam power plant
CON	steam condenser
CP	condensate pump
GEN	generator
GT	gas turbine
HPEC	high-pressure economizer
HPEV	high-pressure evaporator

HPS	high-pressure steam
HPSH	high-pressure superheater
HPP	high-pressure pump
HPT	high-pressure steam turbine
LPEC	low-pressure economizer
LPEV	low-pressure evaporator
LPS	low-pressure steam
LPSH	low-pressure superheater
LPP	low-pressure pump
LPT	low-pressure
NG	natural gas
SGEC	stack gas economizer
ST	steam turbine