PRESSURIZED FLUIDIZED BED COMBUSTION AND GASIFICATION BASED OF A COMBINED CYCLE POWER GENERATION SYSTEM: APPLICATION FOR TURKISH LIGNITE

Murad A. Rahim, Ibrahim Atılgan

Abstract — Combined cycle power generation is currently the most promising technology to generate power at higher plant efficiencies. In this study a simulation system program is proposed for simulation of pressurized fluidized bed gasification and combustion based combined cycle power generation unit, utilizing turkish lignite as a fuel. The effect of pressure ratio, gas turbine inlet temperature, gasifier carbon conversion and the bottoming steam cycle configuration, on the plant performance, for the unit is investigated. System data of the texaco gasifier and the related plant (coal preparation, air separation unit, circulating fluidized bed, gas cleaning, gas turbine, steam turbine and the heat recovery steam generator) are considered. Net power of the combined cycle increasing with increasing overall pressure ratio. By steps of 5% increase of overall pressure ratio affects the net power, gas turbine power and steam turbine power increases about 0.63%, 7.65% and 0.32%, respectively. Gas turbine inlet temperature is increase from 1150 to 1200°C, net power output, gas turbine power output and steam turbine power output increases about 1.42%, 4.0% and 0.22%, respectively. Steam turbine pressure is increased between 70 and 110 bar in step of 10bar; net power output increase about 0.90%, gas turbine power output increase also by 0.50% and steam turbine power output increased about 0.25%. Increase of gasifier carbon conversion affects the net power and net electric efficiency about average increase of 0.03% and 0.063%, respectively. In this case, the optimum output work is considered by increasing the pressure ratio, gas turbine inlet pressure, steam turbine (ST1) inlet pressure, HRSG superheated outlet temperature and higher gasifier carbon conversion.

Keywords — Circulating fluidized bed, Coal Gasification, Lignite, Power Generation, Sensitivity Analysis

1 INTRODUCTION

The availability and accessibility to electrical power will have a profound effect on the economic development, and living standards of any country. Energy provides the power needed for many activities and services that improve health. Energy is also the backbone of industrial processes and production, which is a crucial factor in economic and social development. As we look into the future, we must acknowledge the importance of increasing the access to commercial energy. This will help reduce poverty and improve health throughout the world. Although most of the world have had a chance to benefit from the merits brought by having access to electrical power, people in developing countries have not been as fortunate. In these countries, providing electricity will increase the life expectancy and productivity, and will help in erasing illiteracy [1].

Today, demand for electric power continues to rise steeply due to population growth, economic development, and progressive substitution of alternate technology with clean forms of energy generation. Coal has re-emerged as a major energy source for power generation after having played a subsidiary role to oil during the mid 20th century. Today about 40% of all world electricity is generated from coal; almost double that of its nearest competitor, namely gas (Figure 1).

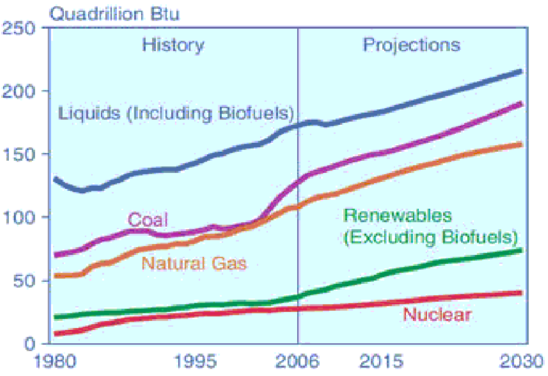

Fig. 1 World energy market as fuel type, 1980-2030 [1]

As can be seen from Fig. 1, coal is the most important fuel source for electricity generation in the

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world today and would also continue to dominate the power station fuel scenario in the foreseeable future [2]. Pressurized Circulating Fluidized Bed (PCFB) combined cycle power generation systems are gaining a lot of attention as a means to produce power efficiently, and in an environmentally friendly manner, using coal and other low grade fuels.

PCFB is one of the most recent members of the fluidized bed family and it is an important unt of the new breed of combined cycle plant concept. PCFB is essentially a circulating fluidized bed which operates at elevated pressures but still maintains all of the advantages of the circulating fluidized bed system. In order of familiarize the reader with pressurized circulating fluidized beds, the CFB and its characteristics are briefly discussed below.

In open literature, research activities are mainly directed towards simple pressurized fluidized bed combustion cycle and gasification of coal based combined cycle power plants have been studied in a good amount of works [3-13]. F. Emun et al., (2010) [3] used Aspen Plus® simulation tool for simulation of integrated gasification combined cycle (IGCC). They used this tool in their study to improve IGCC's efficiency and the environmental performance through an analysis of the operating conditions, together with process integration studies. Pinch analysis principles and process integration insights are then employed to make topological changes to the flow sheet to improve the energy efficiency and minimize the operation costs. Parameter analysis and heat integration was conducted. In this stud, it was observed that the thermal efficiency reached to 45% and significant decrease in CO_2 and SOx. Andries et al., (1997) [4] modified 1.6 MW_{th} pressurized fluidized bed combustion test rig to study experimentally the gasification process and the pressurized combustion of the resulting low calorific value fuel gas. In this study, the experimental results from test rig were obtained from combustion experiments with coal, recalculated flue gas and pure oxygen. The conversion efficiencies and the emission of harmful components measured during these experiments are analyzed and compared with values obtained during combustion and gasification using air. In the work by Nag et al. (1994) [5] an atmospheric and pressurized char combustor is utilized in a similar partial gasification coal based cycle. Here, the heat from the heat recovery steam generator (HRSG) is used for steam generation for the low pressure steam turbine in the bottoming cycle. The extent of coal gasification was fixed in this case, and only one cycle configuration was analyzed, based on the effects of pressure ratio and gas turbine inlet temperature. Robertson et al., (1994) [6] reported on an experimental study of a second generation pressurized fluidized bed combustion pilot plant. The effects of gasifier operating temperature and gas turbine pressure ratio on the combined cycle performance were the target of this experiment. As the combined cycle efficiency is directly depend on the efficiency of the steam cycle, therefore the hot gas outlet temperature from the boiler furnace is a key factor in determining the efficiency of the bottoming cycle. Hamel and krumm, (2001) [7] presented a gasification model in pressurized fluidized bed reactors. Their model included bed and freeboard fluid-dynamics, kinetic for drying, devolatilization and chemical reactions. The components of the reactor, such as the cyclone, the gasifier and pipes, are divided in discrete segments called cells, composed by bubble and emulsion phases. Using this model, they simulated four reactors, from laboratory scale at atmospheric pressure, to commercial scale at high pressures, processing brown coal, peat and sawdust with air, air/steam or oxygen/steam as gasification agent. The model results for overall conversion, temperature and concentration of gaseous species are validated with published experimental data. Roberts and Harris (2006) [8] presented a paper about reactivity of two Australian coals, a bituminous coal and anthracite, for combustion and gasification reactions at pressures between 1 and 20 atm. Work done by Eidensten et al. (1996) [9], where exhaust gas from the gas turbine is fed back into the boiler furnace for further combustion. Wallman and Calesson (1991) [10] studies the combustion kinetics of medium-volatile bituminous coal at pressure of 0.2, 1 and 2 MPa. They did not find any significant effect of pressure on the combustion rates over their range of conditions: Temperature 700-800 °C, coal practice size 0.3-4.8 mm, and O_2 concentration 3-7%. In this case combustion kinetics was mass transfer controlled. This may not be the case in pressurized circulating fluidized bed combustors due to differences in hydrodynamics. Yong et al. (1994) [11] developed the Quartz Wool Matrix technique used to simulate char combustion behavior in the dilute core region of circulating fluidized beds. The Quartz Wool has a high voidage (up to 0.996) which is similar to the combustion environment in large circulating fluidized bed boilers. Issakson et al. (1990) [12] reported some experimental data on the overall performance of a 10 MWth PCFB pilot plant. Sellakumar and Engstrom (1991) [13] presented some details on the effect of operation parameters on the performance of a PCFB unit.

In this article, a pressurized fluidized bed, partial gasification and combustion based combined cycle presented previously by K.M. Mohammed [1] is formulated and applied to a partial gasification fluidized bed combustor combined cycle. Three deferent system configurations are considered. The effect of the degree of coal gasification on the combined cycle performance, and the second law analysis were performed by K.M. Mohammed. In previous work, the char output from gasifier was enter to partial CFB combustor which is gasified and returned back to the combustion chamber on topping cycle. Gas cleaning system was used twice in this case, and this is the main weakness for the economical aspects for the plant. In this article, the slag output from gasifier is mixed with the same coal used in gasifier and combustion them in CFB. This will increase the steam quality and quantity, which is enhance the net power output from the plant and decrease emissions output.

2 SYSTEM DESCRIPTION

Figure 2 represents pressurized circulating fluidized bed gasification and combustion based combined cycle consisting of a simple gas turbine (GE7251 FB) cycle and steam turbine cycle. Inlet air at 15°C is compressed in air compressor, where mass flow rate of air is maintained at 57.46kg/s. Compressed air is heated in the combustion chamber to 1150°C, where it is later fed the gas turbine in topping cycle. The hot products of combustion then expand in the gas turbine, which is coupled to a generator for electricity production.

After expansion in the gas turbine the exhaust gases is passed to a circulating fluidized bed (CFB) furnace, where turkish lignite is burnt. The process generates thermal energy, which is in turn extracted to heat the air. Exhaust gases from the CFB, which is set at 870°C. The optimum operating range for the CFB unit is between 850°C and 950°C, where NO_x emissions are best kept at the lowest level.

3 METHODOLOGY AND ANALYSIS

Table 1 shown the turkish Tunçbilek lignite used in the analysis is assumed to be of the following composition:

Table 1 Proximate and ultimate analyses of Tunçbilek turkish lignite [14].

Compenants	Weight Percentage [%]
Proximate analysis	
Moisture	10
Ash	16
Volatile matter	34
Fixed carbon	50
Ultimate analysis	
C	61.24
H	4.52
N	2.69
S	1.91
O (difference)	29.64

The calorific value (heating value) of coal is given to be: LHV = 22,860.00 kJ/kg.

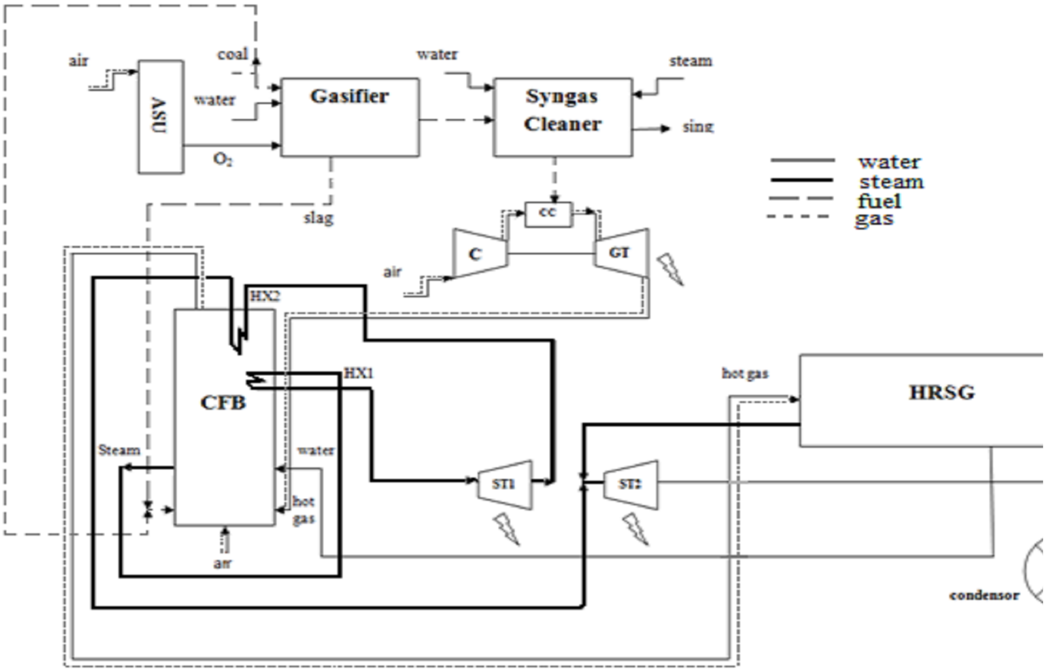


Fig. 2 Schematic diagram of pressurized gasification combined cycle power plant

During this study, the following assumptions are conducted; all systems operate in a steady state condition, the ideal gas principles are applied to air and exhaust gases, the combustion reaction in combustion chamber is complete and the kinetic and potential energy changes are negligible. With the above assumptions, mass, and energy balances for any steady state system can be written as [15]:

$$\sum \dot{m}_i = \sum \dot{m}_e \qquad (1)$$

$$\dot{Q} + \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \qquad (2)$$

where $\dot{Q}$ and $\dot{W}$ are the net heat and work inputs, $\dot{m}$ is the mass flow rate of the fluid stream, h is the enthalpy, the subscripts i and e stand for inlet and exit. Using an energy balance on the HRSG, with an assumed 3% of heat loss taken into an account,
the amount of steam generation can be calculated from:

$$0.97[\dot{m}_{mix}(h_{in,hot} - h_{out,hot})_{HRSG} = \dot{m}_{steam}(h_{in,cold} - h_{out,cold})_{HRSG} \qquad (3)$$

here; $\dot{m}_{mix} = \dot{m}_{fuel} + \dot{m}_{air}$

Based on literatures, generally the fluidized bed gasifier products leave at 1000°C, although this varies based on the gasifier conditions. The high temperature in the gasifier ensures that all volatile matter is gasified. The total amount of carbon gasified is equal to the sum of carbon from volatile matter, and the percentage of fixed carbon assigned. From this, the amount of remaining carbon in char is computed. The temperature of the fuel gas is influenced by factors such as: the coal feed rate, the percentage of gasification, and the pressure level in the gasifier (set equal to the topping cycle pressure ratio). Based on the temperature of the fuel gas leaving the gasifier being maintained at 963°C, the amount of steam input into the gasifier is varied to control the gasifier exhaust temperature. It is assumed that the steam enters the gasifier as saturated vapor. For Texaco gasifier, the composition of the gasified fuel shown on Table 2. (by % volume).

Table 2. The composition of the gasified fuel out from Texaco gasifier by volume %

Compenants	**Volume Percentage [%]**
CO_2	15.87
CO	30.18
H_2	28.08
CH_4	6.059
H_2O	18.46
others	1.351 (neglected in the analysis)

As a result, the partial gasification equation is of the following form [8], which is based on the amagat model for ideal gas mixture:

Coal + air + steam → fuel gas + steam and N_2 + char + sulfur and ash

The compressor provides compressed air to the gasifier, CFB char combustor, and to the combustion chamber where cooling air is required. In addition, as the inputs into the gasifier are varied to maintain the necessary operating conditions, the calorific value of the resulting fuel gas and char also will vary [1]. The work terms and thermal efficiency for the combined cycle are as follows:

Gas cycle net work output:

$$\dot{W}_{net,GT} = \dot{W}_{GT} - \dot{W}_{C} \qquad (6)$$

where, $\dot{W}$ is the work, the subscripts GT and C stand for gas turbine and compressor.

Steam cycle net work output:

$$\dot{W}_{net,ST} = \dot{W}_{ST} - \dot{W}_{P1} - \dot{W}_{P2} \qquad (7)$$

The combined cycle net power output:

$$\dot{W}_{net} = \dot{W}_{net,GT} + \dot{W}_{net,ST} \qquad (8)$$

The heat added:

$$\dot{Q}_{inlet} = \dot{m}_{coal} * LHV_{coal} \qquad (9)$$

where, $\dot{Q}$ is the net heat.

The combined cycle thermal efficiency:

$$\eta_{CC} = \frac{\dot{W}_{net}}{\dot{Q}_{inlet}} \qquad (10)$$

4 Results and discussions

The first stage air compressor inlet conditions were set at 1 atm and 15°C. The exhaust gases temperature at the HRSG exit was assumed fixed at 112°C. A 3% heat loss is assumed in the gas turbine combustion chamber, and the CFB char combustor. The isentropic efficiency of all the working components; air compressor, gas turbine and steam turbine was set at 86%, 92% and 88%, respectively. The high pressure steam turbine inlet conditions were fixed at 80bar and 537°C. The steam turbine reheat conditions were set at 6bar and 537°C .
The condenser pressure was set at 0.068bar. The cycle considered in the detailed analysis is that of

Fig. 4 to Fig. 13. Change of the mass flow, net power output, net electrical efficiency and net heat rate according to design point overall pressure ratio shown through Fig. 4 to Fig. 6. Figures through 7 to 9 show the change of the mass flow, net power output, net electric efficiency and net heat rate with respect of gas turbine inlet temperature. Change of power output, net electric efficiency and heat rate according to high pressure steam turbine (ST1) inlet pressure presented in Fig. 10 to Fig. 11. Effect of gasifier carbon conversion on net electric efficiency and net power is given at Fig. 12.

We note the followings from these results:

- Overall pressure ratio is increased from 11 to 30, fuel mass flow, ambient air mass flow, slag mass flow, raw syngas mass flow, water flow to gasifier and oxygen flow to gasifier decreasing about 7.35%, 7.29%, 7.31%, 7.29% and 8.03%, respectively. Increasing the pressure ratio, results in the CFB char combustor air entering at a higher pressure and temperature. With the percentage of oxygen leaving the char combustor fixed in the analysis, the char combustor exhaust temperature is controlled by increasing the steam generation in the bottoming cycle.
- Net power of the combined cycle increasing with increasing overall pressure ratio. By steps of 5% increase of overall pressure ratio affects the net power, gas turbine power and steam turbine power increases about 0.63%, 7.65% and 0.32%, respectively.
- Net electric efficiency is increasing faster between overall pressure ratio from 11 to 20, but it begin to decrease when the design point overall pressure ratio is raised 20; net electric efficiency is increasing about 0.53%.
- Higher gas turbine inlet temperatures, the fuel mass flow, slag mass flow and raw syngas mass flow increase too. But the total mass flow rate expanding through the gas turbine is lower. However, for a fixed pressure ratio, a higher gas turbine inlet temperature consequently results in the exhaust gases leaving the gas turbine at a higher temperature. This increase in the exhaust gases temperature entering the CFB, dominated the drop in the mass flow rate, and the overall effect is an increase in steam production by the CFB. Ambient air mass flow, slag mass flow, raw syngas mass flow, water flow to gasifier and oxygen flow to gasifier increasing about 7.29%, 7.31%, 7.30%, 7.33% and 7.31%, respectively.
- The increase in steam generation in the bottoming cycle, also results in an increase in the net work production with higher gas turbine inlet temperatures. Unlike the gas turbine net work, the increase in steam turbine net work output is more linear. Gas turbine inlet temperature is increase from 1150 to 1200°C, net power output, gas turbine power output and steam turbine power output increases about 1.42%, 4.0% and 0.22%, respectively.
- Net electric efficiency is increasing with increasing gas turbine inlet temperature. By step 50°C increase of gas turbine inlet temperature affects the net electric efficiency increases about 1.1%.
- Steam turbine pressure is increased between 70 and 110 bar in step of 10bar; net power output increase about 0.90%, gas turbine power output increase also by 0.50% and steam turbine power output increased about 0.25%.
- Steam turbine (ST1) design point inlet pressure is increased between 70 and 110bar in step of 10bar; and it’s shown that, net electric efficiency is increasing about 0.41%.
- Increase of gasifier carbon conversion affects the net power and net electric efficiency about average increase of 0.03% and 0.063%, respectively.

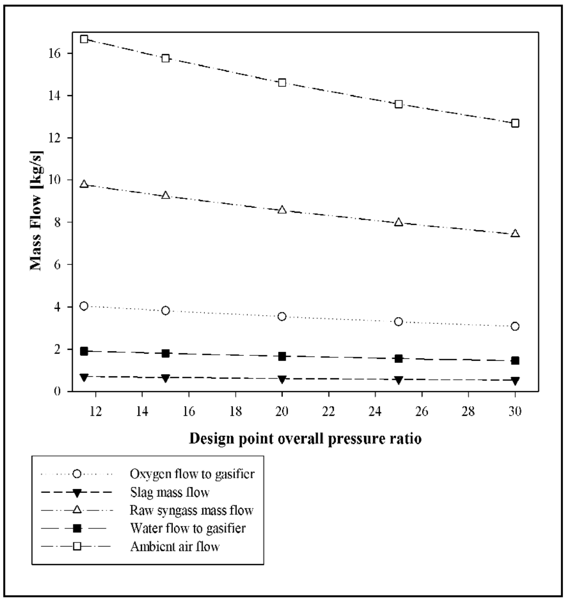
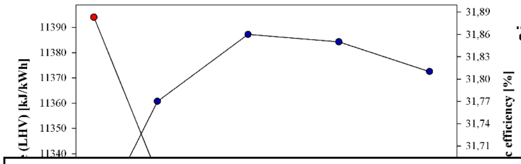


Fig. 4 The effect of overall pressure ratio to various mass flows in a combined cycle



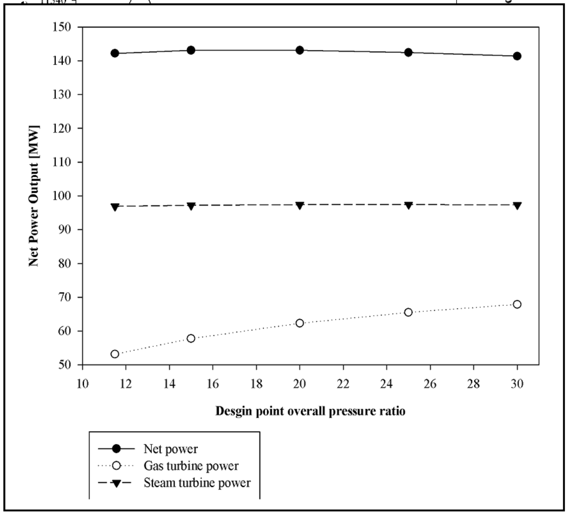


Fig. 5 The effect of pressure ratio on gas turbine, steam turbine and combined cycle power outputs

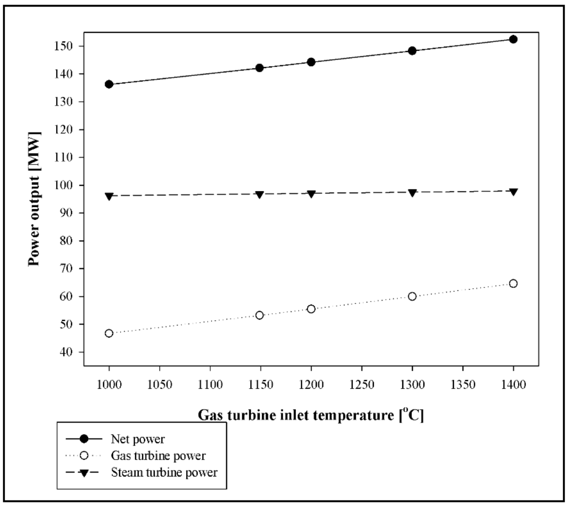


Fig. 8 The effect of gas turbine inlet temperature on gas turbine, steam turbine and net power output

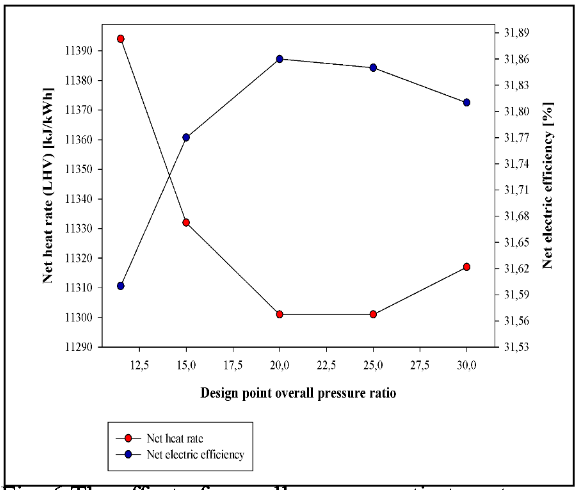


Fig. 6 The effect of overall pressure ratio to net electric efficiency and net heat rate

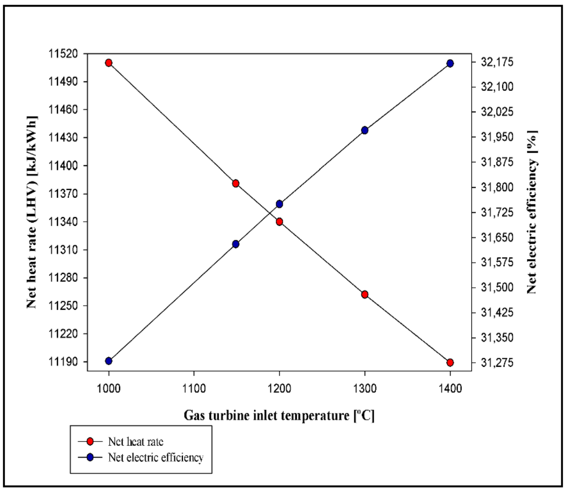


Fig. 9 The effect of gas turbine inlet air to net electric efficiency and net heat rate

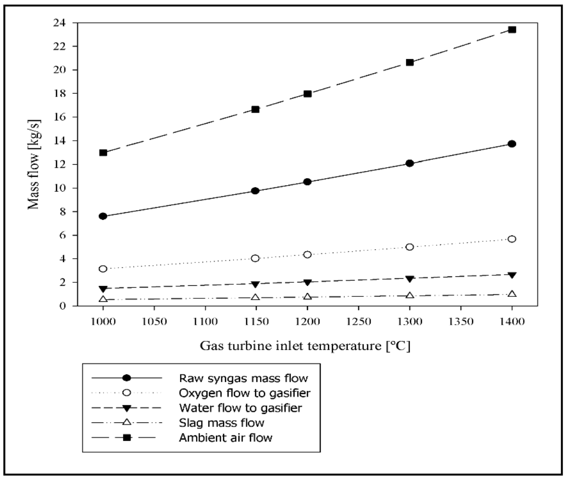


Fig. 7 The effect of gas turbine inlet temperature to various mass flows in a combined cycle

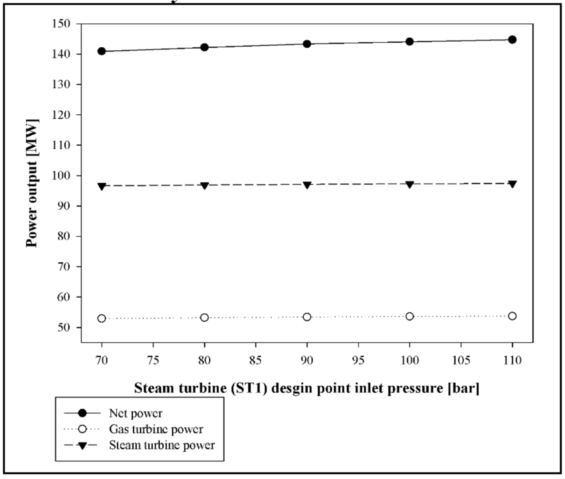


Fig. 10 The effect of steam turbine (ST1) design point inlet pressure to gas turbine, steam turbine and net power output

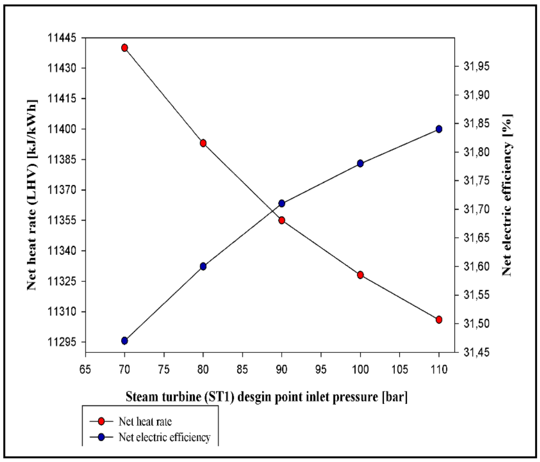


Fig. 11 Effects of steam turbine (ST1) design point inlet pressure on net electric efficiency and net heat rate

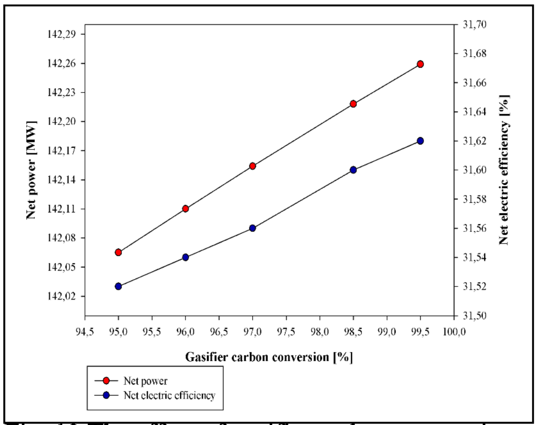


Fig. 12 The effect of gasifier carbon conversion on net electric efficiency and net power output

5 CONCLUSION

A pressurized fluidized bed gasification and combustion based combined cycle configuration simulated by THERMOFLEX packet program is realized. With a higher pressure ratio, there is a more significant drop in enthalpy across the gas turbine, which therefore, results in more work output for a fixed mass flow rate. Even higher pressure ratio and dilution air flow rate require more work from the air compressor, as a combination of a higher gas turbine enthalpy drop, and an increase in mass flow rate, the topping gas turbine net work output increases with pressure ratio. There is a significant drop in the HRSG steam generation by increasing pressure ratio, which results in a slightly drop in the bottoming steam cycle net work output. The increase in topping gas turbine cycle net work output is dominant and the result is that a higher combined cycle net work output is achieved, as the pressure ratio is increased. Based on a pressure ratio of 11, it was found that a minimum gas turbine inlet temperature of 1150°C is required for proper operation of the HRSG. An increase in the gas turbine inlet temperature results in more steam generation in the CFB, and therefore, a higher total steam flow rate in the bottoming cycle.

Both, the gas turbine and steam turbine net work output increases at higher gas turbine inlet temperature. Resulted in the highest steam generation in the bottoming cycle, as the superheater at HRSG outlet temperature and steam turbine inlet pressure (ST1) increases. Steam turbine power output and net power output increases at higher HRSG superheater outlet temperature. Finally, it is found that a higher gasifier carbon conversion is obtained by the combined cycle operation.

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