Performance analysis of mixing syngas from biomass gasification on the combined cycle power plant

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A combined cycle power plant coupled with biomass gasification system is proposed in this present research. The thermodynamic analysis is performed by the impact factor of the mixing ratio and the equivalence ratio. The results show that, with the increase of the mixing ratio from 0 to 50%, the syngas flow from biomass gasification increases from 0 to 54.20 kg/s. The inlet airflow decreases from 654.6 kg/s to 576.3 kg/s. The temperature of the flue gas increases from 586.5 ℃ to 591.4 ℃. Besides, the power output of the gas turbine increases from 260.51 MW to 264.61MW, while, the power output of the steam turbine drops from 131.05 MW to 126.89 MW. Additionally, with the equivalence ratio increasing from 0.20 to 0.40, the H2 composition decreases from 3.01 % to 1.53 % and the CO composition drops rapidly from 23.75 % to 10.44 %. The net calorific value of the syngas decreases from 6709.85 kJ/kg to 3369.03 kJ/kg, the mass flow rate of both the syngas and the flue gas increase from 6.88 kg/s to 9.02 kg/s and from 575.17 kg/s to 601.00 kg/s, respectively. Besides, the power output of the gas turbine increases from 264.49 MW to 270.17 MW, while, the power output of the steam turbine drops from 127.01 MW to 121.28 MW.

Key words*: biomass gasification, syngas, combined cycle power plant, CCPP*

1. Introduction

China is the world's largest energy consumer and the world's largest emitter of carbon dioxide [1]. Since the "double carbon" target was established, it has become a key strategic direction for all industries. Therefore, the development trend of the power industry is mainly from fossil energy to renewable energy. The step of replacing fossil energy sources does not happen overnight. In the process of power structure transformation, coupling traditional fossil energy with renewable energy for power generation is of great significance to gradually increase the proportion of renewable energy in the power system and it will help better promote the energy consumption revolution [2, 3].

As a renewable and sustainable energy source, biomass is receiving increasingly widespread attention for its unique qualities [4]. Biomass comes from organic materials like plant matter and agricultural waste, which can decrease waste and greenhouse gas emissions [5]. According to the report from IEA, biomass accounts for around 10 % of worldwide energy generation [6]. A significant obstacle to the management and disposal of biomass is the waste produced by forestry and agriculture, which amounts to over 140 billion tons annually worldwide [6]. It is anticipated that bioenergy will almost double the amount used to generate power, and it will produce over 1350 TWh in 2030 [7]. Therefore, it's essential to find creative methods that can improve the sustainability and value of using biomass in low-carbon products.

Biomass can be used for power generation, heating, making biofuels, and gasification to produce syngas. Additionally, its direct blending with fossil energy sources is a technology that can be implemented immediately in a relatively short period in almost all coal-fired power plants, without the need for significant investment. It has therefore evolved as a short-term alternative to relieve pressure on fossil fuel use and reduce CO_2, $SO_{x,}$ and NO_x emissions.

A well-known and suitable method for lowering carbon dioxide emissions from coal-fired power plants is biomass co-firing, which substitutes biomass fuel use for fossil fuel during combustion [8]. Xi et al. [9] simulated and compared a novel biomass air-steam circulating fluidized bed gasification cofiring system with the original air gasification cofiring system at various cofiring ratios using Aspen Plus software. Besides, a thorough examination of combustion characteristics, as well as slagging and fouling behaviors, during the cofiring of coal and biomass is conducted by Hariana et al. [10]. Findings indicated that the best combustion performance came from cofiring coal with 25 % biomass. When incorporated into an actual plant, the findings can offer helpful insights regarding cofiring behavior and slagging-fouling tendencies. Qiyan et al. [11] investigated and optimized a 300 MWe co-firing power plant using coal and biomass as co-firing fuels for the carbon capture operational parameters. Zanib and Usman [12] aimed to investigate the potential impacts on the efficiency of a supercritical power plant by utilizing coal and biomass co-firing considering both domestic and imported fuel. The suitability and comparison of various coal blends and renewable biomass fuels were examined. Additionally, according to the economic research of Jin et al. [13], the coal-to-biomass retrofit costs \$ 18.3–73.0 for every ton of carbon reduction and \$ 21.6–806.5 for every kilogram of SO_2 reduction at one-fourth blending ratio.

As an attractive technology, gasification can convert corn straw into syngas, which can then be used by gas-fueled equipment [14]. In various investigation endeavors, researchers have focused on setting up multigeneration systems that use energy from biomass gasification to partially replace fossil fuels. Hao et al. [15] recommended a revolutionary methane-fueled gas turbine power plant. The biomass served as the post-combustion chamber's supplementary fuel. Five important aspects that influence decision-making were taken into consideration during a comprehensive technical investigation of the thermodynamic and economic variables. Ramin et al. [16] compared the supercritical CO_2 system powered by a biomass gasifier and a micro gas turbine with comparable nominal net power output. Research findings indicated that the average net electric output of the entire integrated sCO_2 system was around 126 kW at 100% load, which was about 25% more than that of the micro gas turbine. Junxi et al. [17] combined a biomass gasification power system with solid oxide fuel cells and a micro gas turbine by using a thermodynamic model. Mariaconcetta et al. [7] investigated the biomass gasification model for heat and power, utilizing clean syngas from a downdraft gasifier as fuel for the internal combustion engine and the micro gas turbine, which act as the prime movers. S. Soltani et al. [18] investigated an externally-fired combined cycle power plant integrated with biomass gasification using advanced exergy analysis. Roque et al. [19] presented a combined electric power generation using syngas as fuel from biomass gasification. Results showed that the hybrid system indicated an optimal efficiency of 17.6 %. Yue et al. [20] introduced a new biomass-based gas turbine with a supercritical CO_2 cycle, a modified Kalina cycle, and LNG regasifying subsystems, the LNG regasifying subsystems were equipped with turbines to increase power output. The parametric research findings indicated that the air compressor's pressure ratio had the greatest impact on the system's performance indices.

In this present research, a combined cycle power plant coupled with biomass gasification system is proposed, the syngas from the gasifier is considered to replace part of the natural gas to reduce CO_2 emissions. Due to the organic integration of the traditional combined cycle power plant and biomass gasifier, the equivalence ratio (ER) of the gasifier will affect the composition of syngas, Therefore, it is necessary to study the effect of ER as well as the mixing ratio of syngas on the overall thermal performance of the system. The results of this work provide guidance for the proportion of syngas co-fired in traditional combined cycle power plants (CCPP) under the condition that without need to change the CCPP system power output.

2. System description

The proposed combined cycle power plant coupled with biomass gasification system mainly consisted of the biomass gasifier and the combined cycle power plant (CCPP). The biomass gasifier is an air-blowed, downdraft, fixed-bed gasifier used for producing syngas, and the main components of the syngas are H_2, CO, CO_2, CH_4 and N_2. The biomass was heated and pyrolyzed in the pyrolysis reactor and then was partially oxidized in the gasifier. The produced syngas contain tar, which is difficult to decompose and is filtrated in the filter. Then, the purified syngas is mixed with natural gas before being burned in the combustion chamber (CC) of the CCPP. The CCPP consists of gas turbine (GT), steam turbine (ST), and heat recovery steam generator (HRSG). The original fuel of the traditional CCPP is natural gas. In this proposed combined cycle power plant coupled with biomass gasification system, the syngas from the biomass gasifier is mixed with natural gas to reduce both the use of fossil fuel and the CO_2 emissions.

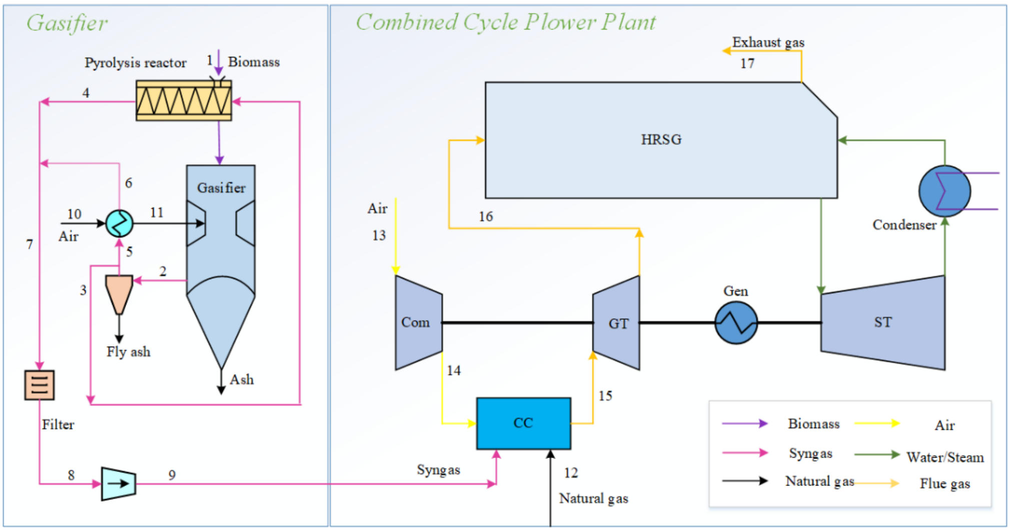

Figure 1. Schematic flow chart of the proposed combined cycle power plant coupled with biomass gasification system

3. Methodology

3.1. Biomass gasification

The biomass gasifier is used to demonstrate a continuous producing syngas with wood chips via preheating, drying, pyrolysis, and gasification. The energy used for preheating and drying is the hot gas from the produced syngas at the outlet of the gasifier. Simultaneously, water turns into vapor and particle surface temperatures rise. During the pyrolysis process, the volatile substances will be released and tar will be decomposed. Following the pyrolysis process, the remaining fixed carbon in the coal particle (char) may react with the surrounding gas during pyrolysis. Because of its large surface area, the porous char particle can absorb gases like CO and CO_2. It will release volatile substances and be of tar. The main reactions in the biomass gasification process are listed in Table 1.

Table 1. Main reactions in the biomass gasification process [21].

No.	Chemical reaction	ΔH^0 (kJ/mol)
1	$C+0.5O_2 \rightarrow CO$	-268
2	$C+O_2 \rightarrow CO2$	-406
3	$C+H2O \rightarrow CO+H_2$	131.4
4	$CO+H_2O \leftrightarrow CO_2+H_2$	-42
5	$C+CO_2 \rightarrow 2CO$	172.6
6	$C+2H_2 \rightarrow CH_4$	-75
7	$CH_4+H_2O \rightarrow CO+3H_2$	206
8	$N_2+3H_2 \leftrightarrow 2NH_3$	-92.4
9	$H_2+S \rightarrow H_2S$	20.63

10	$COS+H_2O \leftrightarrow H_2S+CO_2$	-30.22

The equivalence ratio (ER) indicates the ratio between actual ($\dot{m}_{O_2,in}$) and stoichiometric ($m^{st}_{O_2,in}$) oxygen inlet flow [22].

$$ER = \frac{\dot{m}_{O_2,in}}{m^{st}_{O_2,in}} \tag{1}$$

Another performance measure that has been examined is the lower heating value of syngas (LHV_{syngas}), which is calculated by the quantity of flammable gas, i.e., H_2, CO, CH_4, C_2H_2, C_2H_6, C_3H_8 [23, 24]:

$$LHV_{syngas} = E_{H_2} + E_{CO} + E_{CH_4} + E_{C_2H_2} + E_{C_2H_6} + E_{C_3H_8} \tag{2}$$

where Ei is the energy of the i-th component as follows [23]:

$$E_i = \sigma_i \times LHV_i \tag{3}$$

Where i is 10.792, 12.636, 35.818, 56.469, 64.046, 93.185 for H_2, CO, CH_4, C_2H_2, C_2H_6, C_3H_8.

The calorific value of syngas can be estimated as [25]:

$$\dot{Q}_{syngas} = \dot{m}_{syngas} \times LHV_{syngas} \tag{4}$$

3.2. Combined cycle power plant

For the CCPP, a GT consists of a compressor, a combustion chamber, and a expander. The actual compression work of the compressor is [26]:

$$w_C = \frac{c_p\left(T_{2s}^* - T_1^*\right)}{\eta_C} = \frac{c_p T_1^*\left(\pi^{\frac{k-1}{k}} - 1\right)}{\eta_C} \tag{5}$$

where, T_1^* and T_{2s}^* are the isentropic temperature at the inlet of the compressor and the isentropic temperature at the outlet of the compressor, respectively; c_p is the specific heat at constant pressure, kJ/kg·K; π is the compressor pressure ratio, k is the adiabatic index, η_C is the compressor efficiency,%.

The actual expansion work of the turbine is [27]:

$$w_T = c_p\left(T_3^* - T_{4s}^*\right)\eta_T = c_p T_3^*\left(1 - \frac{1}{\pi_T^{\frac{k-1}{k}}}\right)\eta_T \tag{6}$$

where, T_3^* and T_{4s}^* represent the stagnation temperature at the inlet and outlet of the gas turbine, respectively. π_T is the expansion ratio of the turbine. η_T is the efficiency of the turbine.

The amount of fuel added to the combustion chamber q_f is:

$$q_f = q_T + q_{cl} - q \tag{7}$$

where, q_T is the mass flow rate of flue gas at the inlet of the expander, kg/s; q_{cl} is the air flow rate for air leakage and cooling, kg/s; q is the airflow rate of at the inlet of the compressor, kg/s. For this proposed system, the mixed syngas and natural gas are considered as fuels. Therefore, q_f can be expressed as the sum of the mass flow rate of syngas and the natural gas:

$$q_f = q_{\mathrm{H_2}} + q_{\mathrm{CH_4}} \tag{8}$$

The power output of a gas turbine will drive the compressor and the generator, so the power output for the GT can be expressed as the difference between the output power of the gas turbine w_{T} and the consumed power of the compressor w_{C} [28]:

$$w_{gt} = (w_T - w_C)\eta_{\mathrm{mgt}} \tag{9}$$

where the η_{mgt} represents the mechanical efficiency of the GT,

The total power output for the CCPP can be expressed as the sum of the output power of the gas turbine w_{gt} and the output power of the steam turbine w_{st}:

$$w_e = w_{gt} + w_{st} \tag{10}$$

4. Model validation

To guarantee the accuracy of the simulation output, the system models are checked in this section. The biomass gasifier and the CCPP are modeled by EBSILON® Professional. Ebsilon is developed by the German STEAG power group, which is a visual thermal system modeling software mainly used for thermal balance calculation of thermal systems. This software is widely used in the design, optimization, renovation, and operation process of power plant thermal systems. By using this software, various schemes can be easily and quickly designed, scheme parameters can be optimized, and variable operating conditions can be simulated during the feasibility study stage of the project [29].

4.1. Gasifier validation

For the model of the biomass gasifier, comparisons are done for the predicted gas composition of the produced syngas between the proposed simulated model and the experimental results provided by Jesper et al. [30]. The comparison of syngas composition between experimental data and the simulated results is shown in Table 2. It can be seen that there are small gaps between the experimental and simulated values. The significant difference in the composition of H_2 content is due to the high moisture content of the fuel used in the experiment. Hence, it is believed that the model of the gasifier is validated and the model can be further used for parameter analysis.

Table 2. The comparison of syngas composition between experimental data and the simulated results.

Item	Ref. [30]	Sim.
H_2 (vol %)	30.5	33.67
CO (vol %)	19.6	17.91
CO_2 (vol %)	15.4	14.80
CH_4 (vol %)	1.16	1.17
N_2 (vol %)	33.3	32.45
LHV (MJ/kg)	6.19	6.58

The model of the traditional CCPP is named M701F from the Mitsubishi Corporation, and the model of the CCPP is also modeled by the software of EBSILON® Professional. The comparison of CCPP between the designed value and the simulated value is shown in Table 3. It can be seen that the model of the CCPP is validated and the model can be further used for optimization.

Table 3. The comparison of CCPP between the designed value and the simulated value.

Items	Designed value	Simulated value	Differences (%)
The pressure of the high-pressure steam (MPa)	9.98	9.98	0
The temperature of the high-pressure steam (℃)	566.0	568.0	0.35
The mass flow range of the high-pressure steam (kg/s)	79.14	81.22	2.56
The pressure of the reheated steam (MPa)	3.37	3.37	0
The temperature of the reheated steam (℃)	538.0	538.5	0.09
The mass flow range of the reheat steam (kg/s)	89.61	91.21	1.75
The pressure of the low-pressure steam (MPa)	0.43	0.46	6.52
The temperature of the low-pressure steam (℃)	246.0	246.0	0
The mass flow range of the low-pressure steam (kg/s)	13.64	14.2	3.94
Power output (MW)	390.0	390.0	0
The temperature of the flue gas (℃)	586.0	586.5	0.08

The temperature of the exhaust gas (℃)	90.0	90.9	0.99

5. Results and discussion

In this section, the thermodynamic analysis of the proposed combined cycle power plant coupled with biomass gasification system is performed. The mixing ratio (MR) refers to the ratio between the replaced renewable energy and the conventional fossil fuel (natural gas) used by the CCPP. The energy needed by the CCPP at 100% power load can be calculated by the multiplication of the natural gas lower heat value and mass flow rate of natural gas. For example, when the MR=10 %, it means that 10 % of the energy will be provided by biomass. The parameters of replaced energy data under different mixing ratios are listed in Table 4.

Table 4. The parameters of replaced energy data under different mixing ratios.

Items	Mixing ratio (%)					
	0	10	20	30	40	50
Replaced energy (MJ)	0	71.41	142.82	214.23	285.64	357.04
Mass flow rate of syngas (kg/s)	0	10.84	21.68	32.52	43.36	54.20
Mass flow rate of biomass (kg/s)	0	4.81	9.62	14.43	19.24	24.05

Additionally, the mass flow rates of the syngas and natural gas vary with the mixing ratio as shown in Figure 2. It can be seen that, with the increase of the mixing ratio from 0 to 50%, the mass flow rate needed for the natural gas decreased from 14.60 kg/s to 6.98 kg/s. At the same time, the mass flow rate of the syngas from biomass gasification will increase form 0 to 54.20 kg/s. The total mass flow rate of the fuel ($m_{\text{syngas}}+m_{\text{natual gas}}$) increased from 14.60 kg/s to 61.18 kg/s. The reason why the decreased natural gas flow is much smaller than the increased syngas flow at a specific mixing ratio is that the *NCV* of syngas is 3365.68 kJ/kg, which is much lower than that of natural gas (48913.6 kJ/kg).

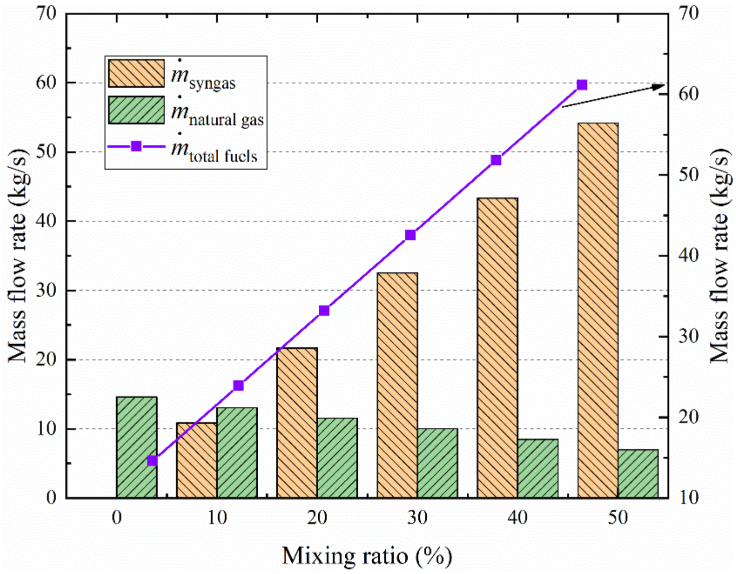

Figure 2. The mass flow rates of the syngas and natural gas vary with the mixing ratio.

The mass flow rates of the inlet air and exhaust gas vary with the mixing ratio as shown in Figure 3. It can be seen that, with the mixing ratio raised from 0 to 50 %, the mass flow rate of the inlet air decreased from 654.6 kg/s to 576.3 kg/s. For the reason that, the natural gas (CH_4) is replaced by syngas (H_2+CO), the chemical equivalence ratio of complete combustion for methane is 2, ($CH_4+2O_2=CO_2+2H_2O$), where it is 1/2 ($2H_2+O_2=2H_2O$; $2CO+O_2=2CO_2$) for H_2 and CO. Hence, when considering the replacement of the natural gas by syngas, the oxygen needed for completing combustion will be reduced to 1/4 of the original mass flow rate. Additionally, the mass flow rate of the flue gas will also be decreased. The significant of reducing the gases flow will help to cut the equipment's size and the initial investment.

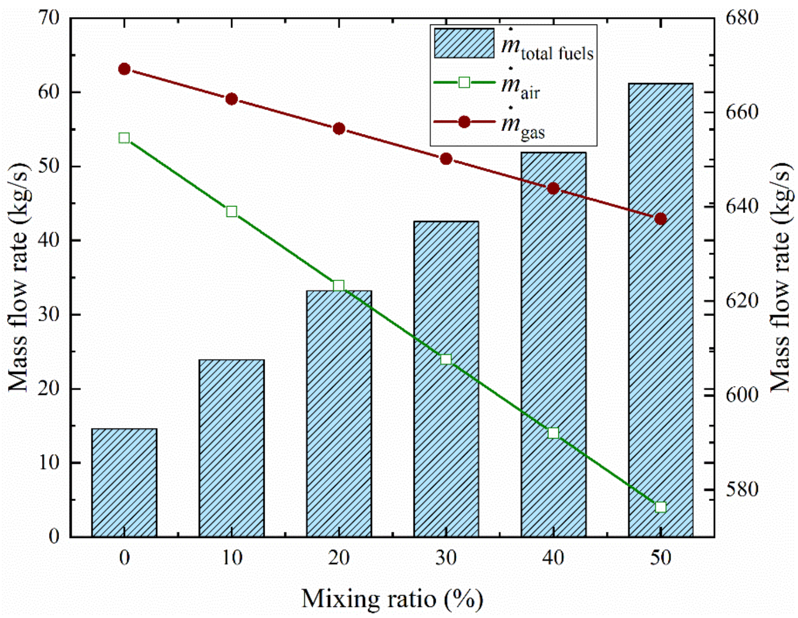

Figure 3. The mass flow rates of the inlet air and exhaust gas vary with the mixing ratio.

The temperature and the mass flow rate of the flue gas (outlet of the expander) vary with the mixing ratio as depicted in Figure 4. It clearly indicated that, with the mixing ratio increasing and the mass flow rate of the flue gas decreasing, the temperature of the flue gas will increase from 586.5 ℃ to 591.4 ℃.

The produced syngas from biomass gasification mainly contains CO, H_2 and N_2, with the increasing of the mixing ratio, the consumption of the air will drop rapidly, therefor the mass flow rate of the flus gas will fall. Besides, with the inlet air temperature increasing, the exhaust has more work capacity, then, gain the power of the GT.

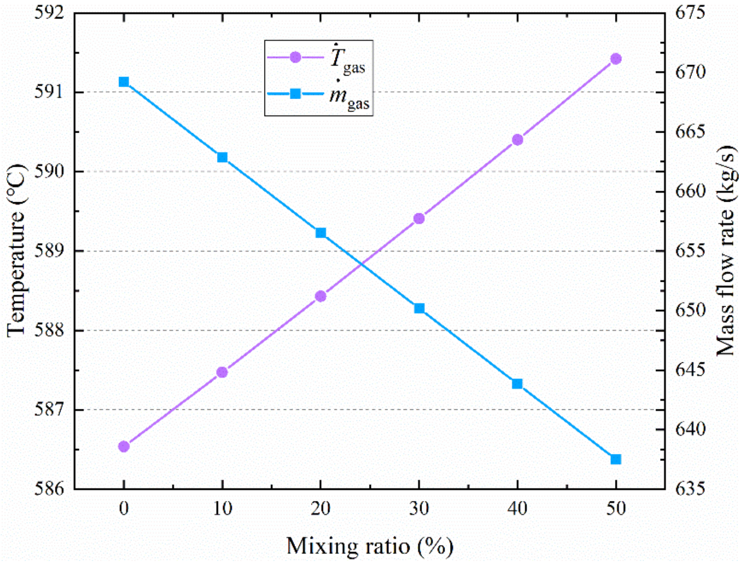

Figure 4. The temperature and the mass flow rate of the flue gas (outlet of the expander) vary with the mixing ratio.

The power outputs of the GT and ST vary with the mixing ratio presented in Figure 5. It can be observed that the power output of the GT will increase from 260.51 MW to 264.61MW with the mixing ratio rising. Besides, the total power output is fixed during the simulation, hence, the power output of ST will drop from 131.05 MW to 126.89 MW.

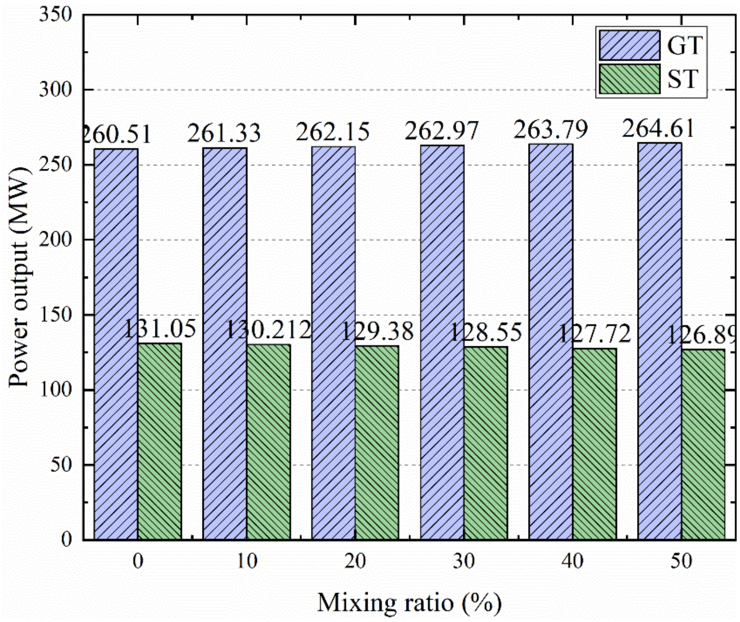

Figure 5. The power outputs of the GT and ST vary with the mixing ratio.

As we all know, a different parameter of the *ER* leads to differences in the composition of syngas. The biomass gasifier is connected with the CCPP, hence, the changing syngas composition will impact the thermodynamic performance of the CCPP. Based on this, it is significantly necessary to analyze the impact of *ER* on the performance of CCPP. The composition of the syngas varies with the *ER* as shown in Figure 6. It can be seen that, with the *ER* increasing from 0.20 to 0.40, the N_2 composition increases, and the CO composition drops rapidly from 23.75 % to 10.44 %. Besides, the H_2 composition slowly decreases from 3.01 % to 1.53 %.

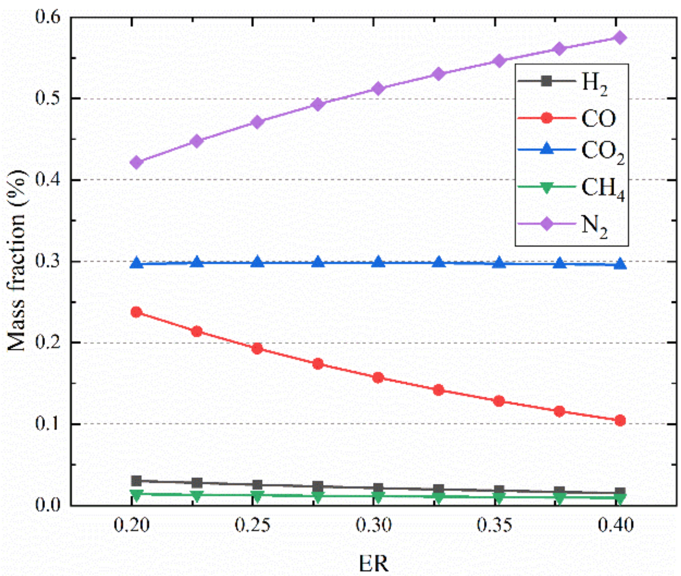

Figure 6. The composition of the syngas varies with the *ER*.

The mass flow rate and the *NVC* of the syngas vary with the *ER* as shown in Figure 7. It can be observed that the NCV decreases with the ER rising from 6709.85 kJ/kg to 3369.03 kJ/kg, and the mass flow rate has the opposite trend. The reason is that higher ER will increase the consumption of air, increasing the composition of nitrogen in syngas. The mass flow rates of the syngas and the flue gas vary with the *ER* as depicted in Figure 8. It can be concluded that the mass flow rate of both the syngas and the flue gas will increase from 6.88 kg/s to 9.02 kg/s and from 575.17 kg/s to 601.00 kg/s, respectively.

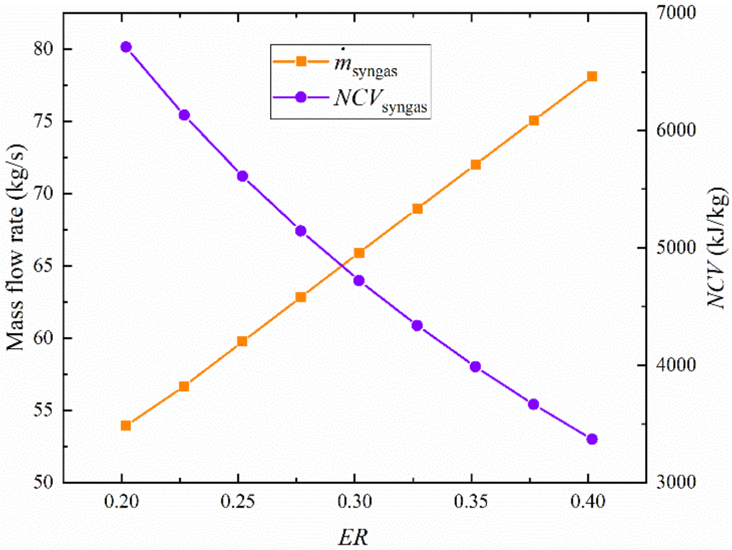

Figure 7. The mass flow rate and the *NVC* of the syngas vary with the *ER*.

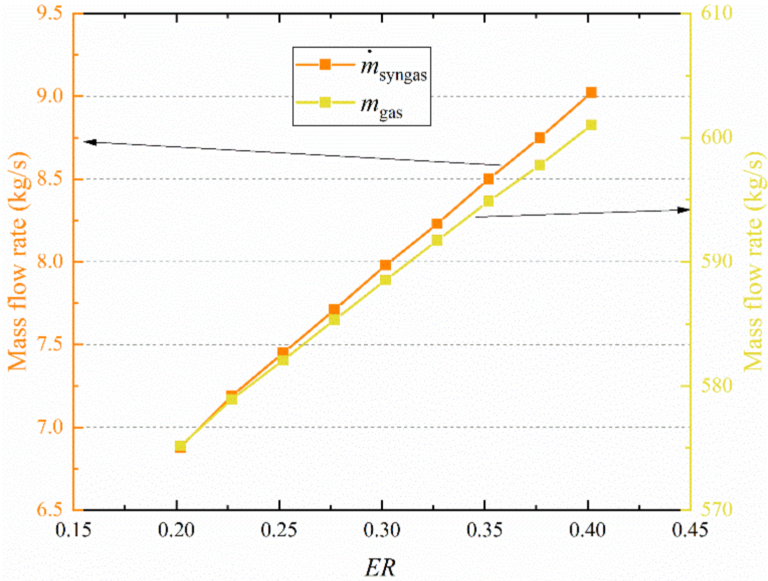

Figure 8. The mass flow rate of the syngas and the flue gas vary with the *ER*.

The power outputs of GT and ST vary with the *ER* as shown in Figure 9. It can be clearly concluded that with the ER increasing from 0.20 to 0.40, the power output of GT will increase from 264.49 MW to 270.17 MW, and the power output of ST will drop from 127.01 MW to 121.28 MW. Based on the previous analysis, the reason is that with the ER increasing, the NCV_{syngas} drops. Additionally, the mass flow rate needed of syngas and the flue gas gained. The temperature of the flue gas is reduced, which further leads to drops in the ST power output.

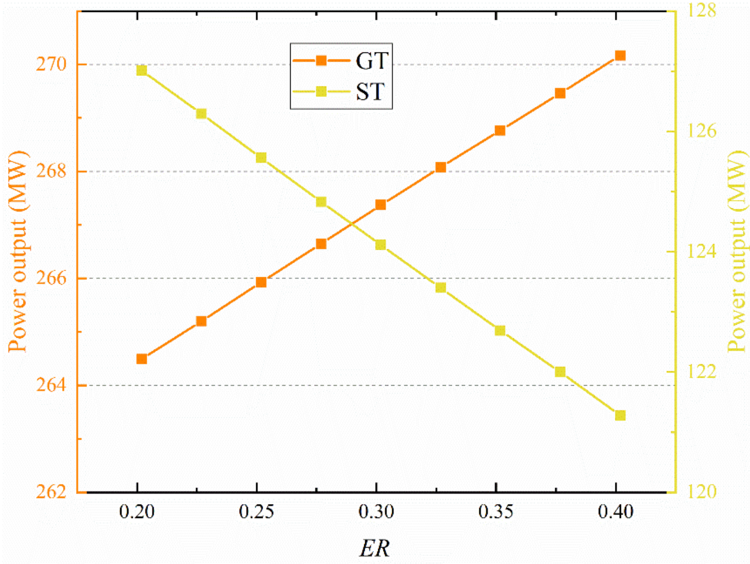

Figure 9. The power outputs of GT and ST vary with the *ER*.

6. Conclusion and recommendations

In this present research, a combined cycle power plant coupled with biomass gasification system is proposed. The thermodynamic analysis is performed by the impact factor of the mixing ratio and the ER. The conclusions are summarized as:

With the increase of the mixing ratio from 0 to 50%, the mass flow rate of the natural gas decreased from 14.60 kg/s to 6.98 kg/s, and the mass flow rate of the syngas from biomass gasification increased from 0 to 54.20 kg/s. Besides, the inlet airflow decreased from 654.6 kg/s to 576.3 kg/s, and the temperature of the flue gas will increase from 586.5 ℃ to 591.4 ℃. Moreover, the power output of GT increased from 260.51 MW to 264.61MW, while, the power output of ST dropped from 131.05 MW to 126.89 MW.

Additionally, with the ER increasing from 0.20 to 0.40, the H_2 composition decreased from 3.01 % to 1.53 %. The CO composition dropped rapidly from 23.75 % to 10.44 %. Besides, the *NCV* of the syngas decreased from 6709.85 kJ/kg to 3369.03 kJ/kg. Besides, the mass flow rate of both the syngas and the flue gas will increase from 6.88 kg/s to 9.02 kg/s and from 575.17 kg/s to 601.00 kg/s, respectively. Moreover, the power output of GT increased from 264.49 MW to 270.17 MW, while, the power output of ST dropped from 127.01 MW to 121.28 MW.

Mixing syngas from biomass gasification on the CCPP can reduce the consumption of fossil fuels and lower carbon emissions. While, the flame temperature and the ignition delay time of syngas is different than that of natural gas. When the mixing ratio of syngas in the fuel is high, the reactivity of the fuel will change. Therefore, it is necessary to test the stability of combustion chamber usage and exhaust emissions, and redesign or optimize traditional combustion chambers and combustion systems.

Nomenclature

CCPP: Combined Cycle Power Plant

ER: Equivalence Ratio

GT: Gas Turbine

HRSG: Heat Recovery Steam Generator

MR: Mixing Ratio

NCV: Net Calorific Value

ST: Steam Turbine

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