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Thermodynamic Analyses of Biomass Post-Firing and Co-Firing Combined Cycles

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Abstract: In the present work, the results are reported of energy and exergy analyses of three biomass-related processes for electricity generation: externally fired biomass combined cycle, biomass integrated co-firing combined cycle and biomass integrated post-firing combined cycle. The energy efficiency for the biomass integrated post-firing combined cycle is 3% to 6% points higher than for the other cycles. The energy and exergy efficiencies are maximized for the three configurations at particular values of compressor pressure ratio, and increase with gas turbine inlet temperature. As pressure ratio increases, the mass of air per mass of steam decreases for biomass integrated post-firing combined cycle, but pressure ratio has little influence on the ratio of mass of air per mass of steam for the other cycles. The gas turbine exergy efficiency is the highest for the three configurations. The combustion chamber for the co-firing cycle exhibits the highest exergy efficiency and that for the post-firing cycle the lowest.

Keywords: Energy; Exergy; Gasification; Combined cycle; Biomass.

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1. Introduction

There are many types of biomass gasification systems [1, 2, 3, 4]. Biomass integrated gasification combined cycles have the potential to provide electricity efficiently, cost-effectively and cleanly [5, 6], but research is still needed to enhance performance [7, 8, 9]. Many factors affect the performance and economics of co-fired combined cycles [7].

Several biomass gasification configurations exist. The externally fired combined cycle (EFCC) can utilize biomass only as a fuel and does not require filters, but it uses a low calorific value fuel and has a relatively low energy efficiency [10, 11]. The co-firing combined cycle fires various fractions of natural gas and biomass and has a reasonable efficiency [12, 13], while mitigating some of the potential challenges when turbines are fired with low calorific fuels, e.g., de-rating [14, 15].

The aim of the present investigation is to enhance understanding of the thermodynamic performance for three biomass-fired combined cycles: externally fired combined cycle (EFCC), biomass integrated co-fired combined cycle (BICFCC) and post-firing combined cycle (BIPFCC). The latter cycle is efficient and of potential interest for repowering gas turbine plants having a gas turbine with a high energy efficiency (40%) and low discharge temperature (440–480 °C). The effects of design parameters on the performance of the cycles are examined.

2. Descriptions of systems

The biomass-fired combined cycles considered all include steam and gas turbine cycles [10] and are as follows:

- EFCC (Fig. 1): Wood fuel is input to the gasifier, and producer gas from the gasifier and heated air from the gas turbine enter the combustion chamber. Exhaust gases from the combustion chamber heat the compressed air in a heat exchanger and then produce steam for the steam cycle in a heat recovery steam generator (HRSG).
- BICFCC (Fig. 2): This cycle uses a fuel mix of natural gas and biomass (wood) [12]. Air exiting the compressor passes through the pre-heater to the combustion chamber. Natural gas fuel is input to the combustion chamber. The producer gas from a downdraft gasifier is conveyed to the post-combustion unit where it mixes with the combustion gases from the gas turbine. Combustion exhaust gases from the post combustion unit preheat the air flow and pass through a HRSG, in which steam for the steam cycle is produced.
- BIPFCC (Fig. 3): This cycle also uses a fuel mix of natural gas and biomass (wood). The producer gas from a downdraft gasifier flows to the post-combustion unit, where it is

combusted using the oxygen content of the combustion gases exiting the gas turbine. Unlike Fig. 2 the exhaust gases from post combustion unit flow to the HRSG.

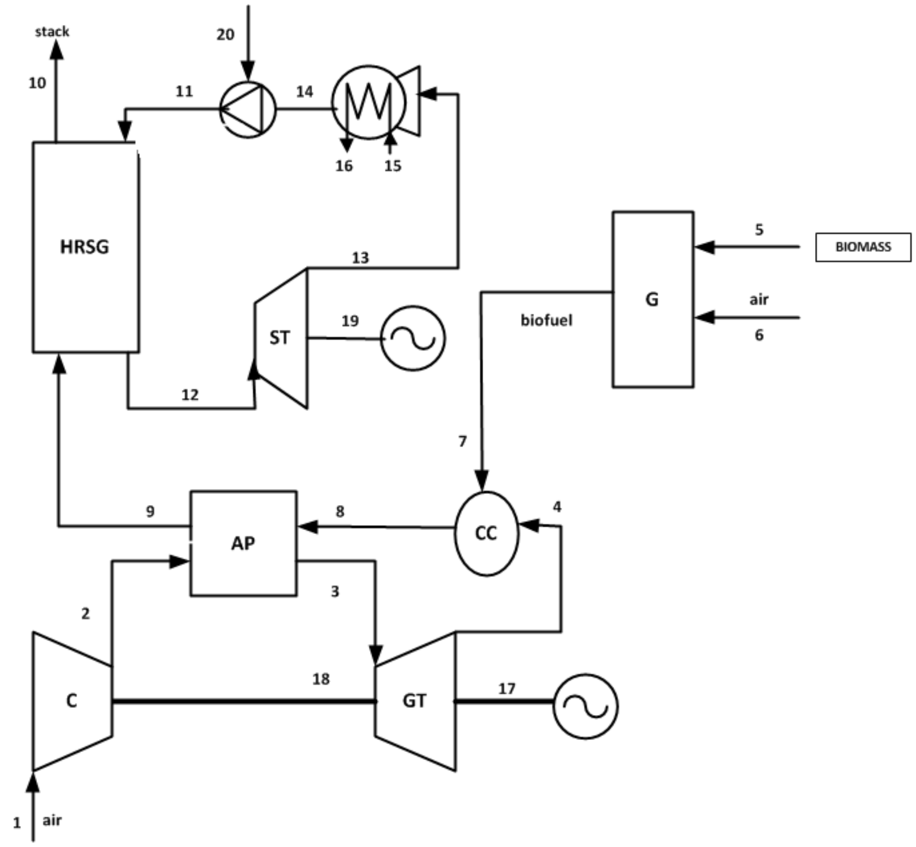

Fig. 1. Externally fired combined cycle.

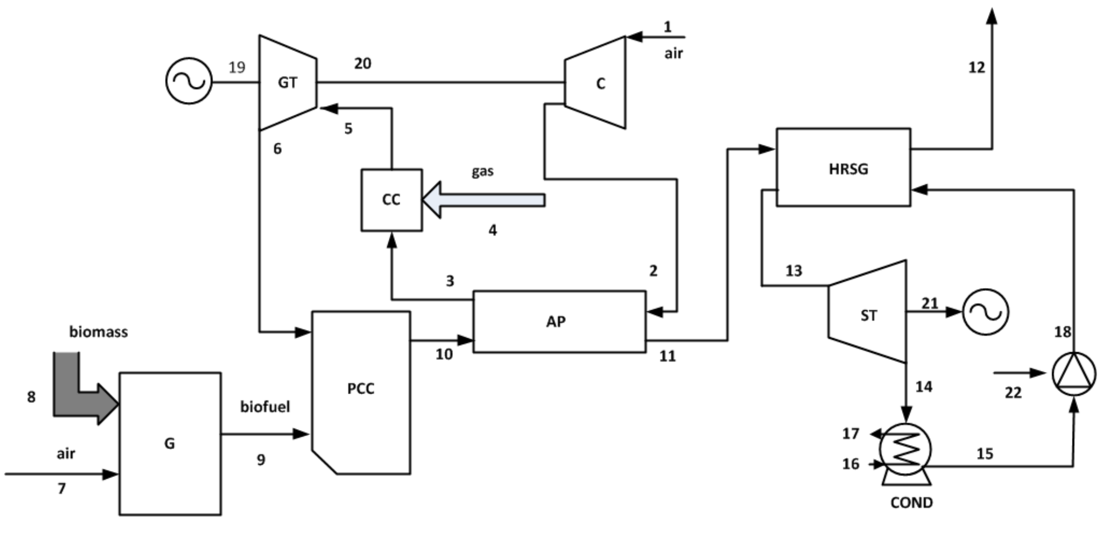

Fig. 2. Biomass integrated co-fired combined cycle.

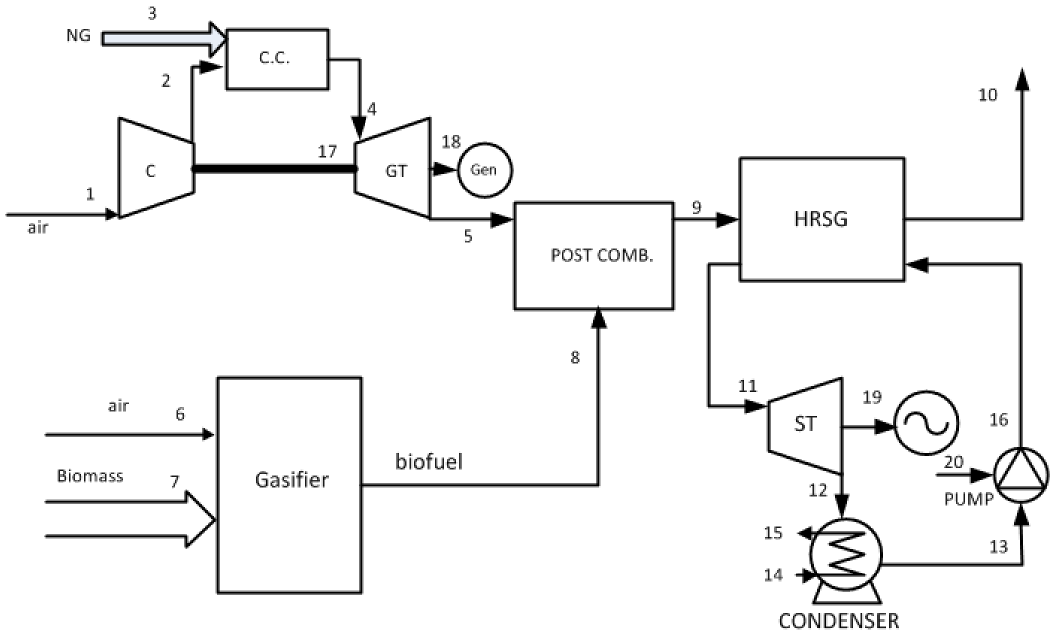

Fig. 3. Biomass integrated post-firing combined cycle.

3. Analyses

Numerous simplifications and assumptions are applied in the analyses. Air (79% nitrogen and 21% oxygen by vol.) enters the compressor at atmospheric conditions, i.e., P_1 = 101.325 kPa and T_1 = 298 K. The dry biomass fuel (wood) has a gravimetric composition of C: 50%, H: 6% and O: 44%, a calorific value of 449,568 kJ/kmol [16], and a 20% moisture content on a mass basis. Complete combustion occurs in the combustion chamber adiabatically and the pressure drop is 1%. The gasification equivalence ratio is 0.4188. The HRSG inlet temperature is 940 K, the HRSG pinch point temperature difference is 10 K, and the maximum steam temperature ($T_{MAX,\ ST}$) is 850 K. The maximum pressure in the steam cycle (P_{MAX}) is 80 bar and the condenser pressure is 0.08 bar, while the minimum allowed steam quality (x_{out}) is 0.9. The isentropic efficiency for the compressor ($\eta_{is,C}$) is 0.87 [11] and for the gas turbine ($\eta_{is,GT}$) is 0.89 [11], while the isentropic efficiency for the steam turbine ($\eta_{IS,ST}$) is 0.9 [12] and for the pump ($\eta_{is,P}$) is 0.8. Pressure drops in heat exchanger at the cold and hot sides are 3% and 1.5%, respectively, of the inlet pressures [11, 17].

The performances of the cycles are assessed considering mass, energy and exergy balances [18, 19, 20, 21], and chemical equilibrium for gasification [10, 22]. An analysis by the authors of the EFCC is provided elsewhere [10] and the same analysis approach is applied for the BICFCC and BIPFCC. The definition for exergy of fuel and exergy of product for three configurations are given in tables 2-4. Cycle energy and exergy efficiencies, respectively, are determined as follows:

$$\eta = \frac{\dot{W}_{net,cycle}}{\dot{m}_{fuel} LHV_{fuel}} \tag{1}$$

$$\varepsilon = \frac{\dot{W}_{net,cycle}}{\dot{E}_F} \tag{2}$$

The gasification results are validated by comparing them (see Table 1) with results from other experimental [23] and theoretical [22] studies, showing good agreement.

Table 1

Comparison of gasification constituent breakdown (in %) for model and experimental approaches, considering gasification at 800 ^{o}C of wood with 20% moisture

Constituent	Present model	Experiment [23]	Zainal equilibrium model [22]
H_2	18.01	15.23	21.06
CO	18.77	23.04	19.61
CH_4	0.68	1.58	0.64
CO_2	13.84	16.42	12.01
N_2	48.7	42.31	46.68
O_2	0.00	1.42	0.00

Table 2

Fuel and product exergy definitions for EFCC.

Component	Exergy of fuel	Exergy of product
Compressor	$\dot{E}_{18}$	$\dot{E}_2$-$\dot{E}_1$
Air Pre-heater	$\dot{E}_8$-$\dot{E}_9$	$\dot{E}_3$-$\dot{E}_2$
Gas Turbine	$\dot{E}_3$-$\dot{E}_4$	$\dot{E}_{17}$+$\dot{E}_{18}$
Combustion Chamber	$\dot{E}_7$	$\dot{E}_8$-$\dot{E}_4$
Gasifier	$\dot{E}_5$+$\dot{E}_6$	$\dot{E}_7$
HRSG	$\dot{E}_9$-$\dot{E}_{10}$	$\dot{E}_{12}$-$\dot{E}_{11}$
Steam Turbine	$\dot{E}_{12}$-$\dot{E}_{13}$	$\dot{E}_{19}$
Condenser	$\dot{E}_{13}$-$\dot{E}_{14}$	$\dot{E}_{16}$-$\dot{E}_{15}$
Pump	$\dot{E}_{20}$	$\dot{E}_{11}$-$\dot{E}_{14}$

Table 3

Fuel and product exergy definitions for BICFCC.

Component	Exergy of fuel	Exergy of product
Compressor	$\dot{E}_{20}$	$\dot{E}_2$-$\dot{E}_1$
Air Pre-heater	$\dot{E}_{10}$-$\dot{E}_{11}$	$\dot{E}_3$-$\dot{E}_2$
Gas Turbine	$\dot{E}_5$-$\dot{E}_6$	$\dot{E}_{19}$+$\dot{E}_{20}$
Combustion Chamber	$\dot{E}_4$	$\dot{E}_5$-$\dot{E}_3$
Post Combustion Chamber	$\dot{E}_9$	$\dot{E}_{10}$-$\dot{E}_6$
Gasifier	$\dot{E}_7$+$\dot{E}_8$	$\dot{E}_9$
HRSG	$\dot{E}_{11}$-$\dot{E}_{12}$	$\dot{E}_{13}$-$\dot{E}_{18}$
Steam Turbine	$\dot{E}_{13}$-$\dot{E}_{14}$	$\dot{E}_{21}$
Condenser	$\dot{E}_{14}$-$\dot{E}_{15}$	$\dot{E}_{17}$-$\dot{E}_{16}$
Pump	$\dot{E}_{22}$	$\dot{E}_{18}$-$\dot{E}_{15}$

Table 4

Fuel and product exergy definitions for BIPFCC.

Component	Exergy of fuel	Exergy of product
Compressor	$\dot{E}_{17}$	$\dot{E}_2$-$\dot{E}_1$
Gas Turbine	$\dot{E}_4$-$\dot{E}_5$	$\dot{E}_{17}$+$\dot{E}_{18}$
Combustion Chamber	$\dot{E}_3$	$\dot{E}_4$-$\dot{E}_2$
Post Combustion Chamber	$\dot{E}_8$	$\dot{E}_9$-$\dot{E}_5$
Gasifier	$\dot{E}_6$+$\dot{E}_7$	$\dot{E}_8$
HRSG	$\dot{E}_9$-$\dot{E}_{10}$	$\dot{E}_{11}$-$\dot{E}_{16}$
Steam Turbine	$\dot{E}_{11}$-$\dot{E}_{12}$	$\dot{E}_{19}$
Condenser	$\dot{E}_{12}$-$\dot{E}_{13}$	$\dot{E}_{15}$-$\dot{E}_{14}$
Pump	$\dot{E}_{20}$	$\dot{E}_{16}$-$\dot{E}_{13}$

4. Results and discussion

4.1. Relations between performance and operating parameters

The effect on cycle performance is investigated for various operating parameters. For the BICFCC the amount of natural gas is fixed at 0.01 kmol/s. Fig. 4 shows the variation in energy efficiencies of the cycles with pressure ratio. The BIPFCC efficiency is 3% and 6% points higher than the corresponding BICFCC and EFCC efficiencies, respectively. As pressure ratio changes, all efficiencies are observed to be maximized at particular values of the gas turbine inlet temperature. Nonetheless, the BIPFCC and BICFCC have the lowest and highest optimum pressure ratios, respectively, for a fixed gas turbine inlet temperature (TIT = 1400 K).

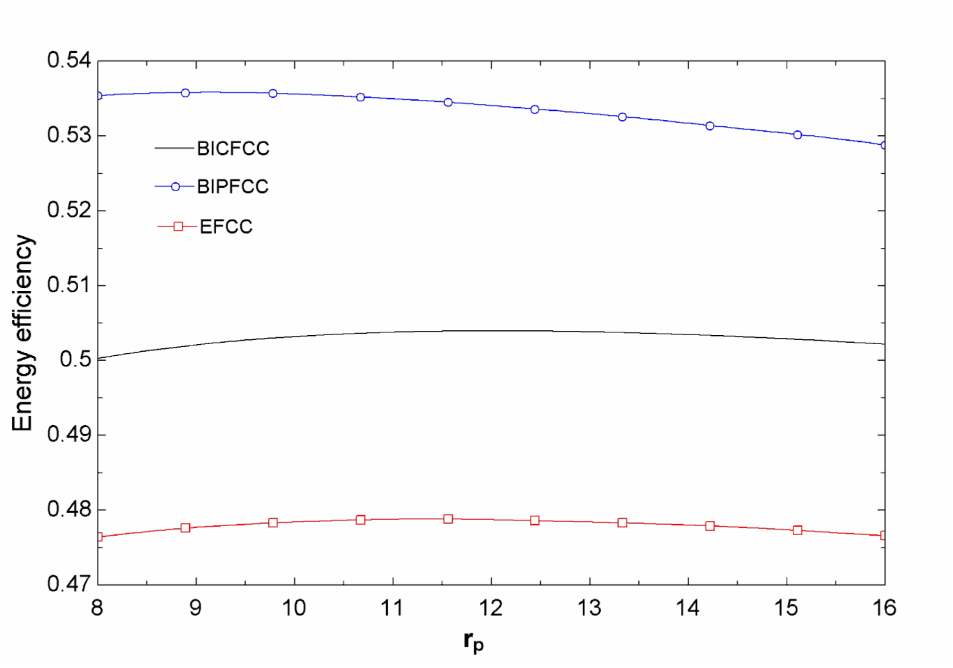

Fig. 4. Variation of cycle energy efficiencies with pressure ratio (TIT = 1400 K).

A similar result is observed for the cycle exergy efficiencies in Fig. 5. The BIPFCC exergy efficiency is about 6% and 10% points higher than the BICFCC and EFCC exergy efficiencies, respectively, mainly because the biomass fired systems have comparatively lower efficiencies. Much less biomass is used in the BIPFCC than the BICFCC.

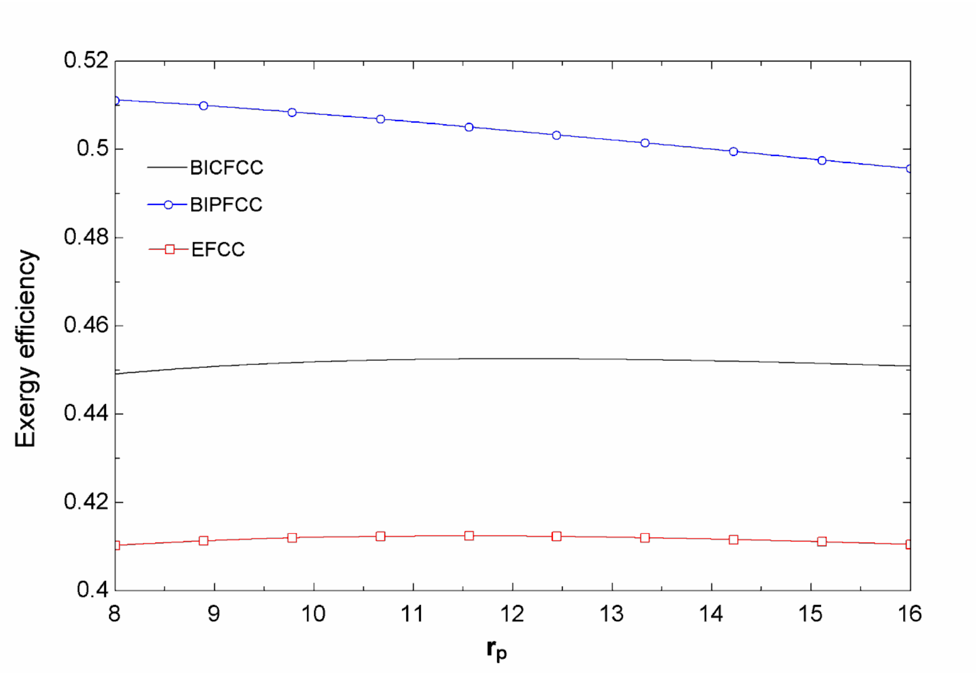

Fig. 5. Variation of cycle exergy efficiencies with pressure ratio (TIT = 1400 K).

Figs. 6 and 7 show the variations in the energy and exergy efficiencies of the cycles with gas turbine inlet temperature (TIT) for a compressor pressure ratio of 9. The efficiencies increase with TIT.

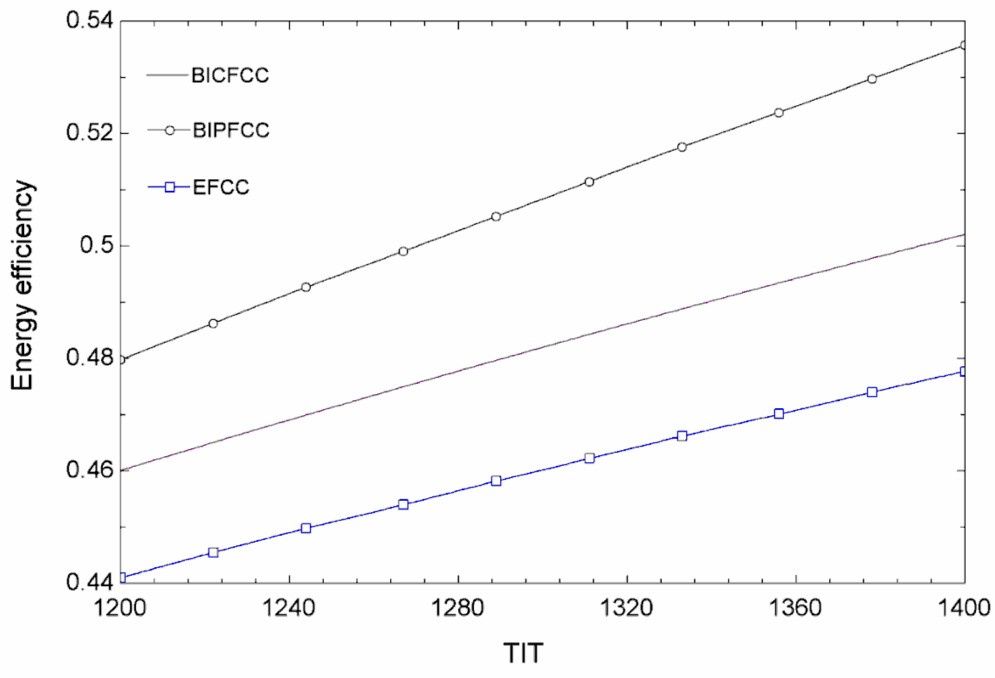

Fig. 6. Variation of cycle energy efficiencies with gas turbine inlet temperature ($r_p = 9$).

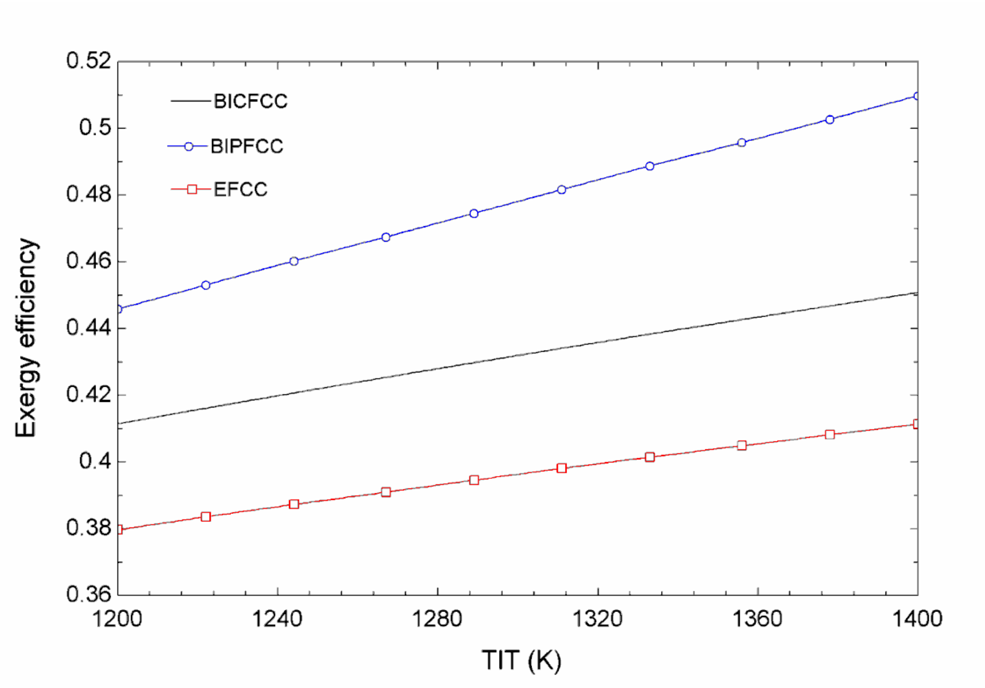

Fig. 7. Variation of cycle exergy efficiencies with gas turbine inlet temperature ($r_p = 9$).

Fig. 8 shows the variation of mass of air per mass of steam for the three cycles with pressure ratio changes, for TIT = 1400 K. As r_p increases, the mass of air per mass of steam decreases for the BIPFCC, but pressure ratio has little influence on the ratio for the EFCC and BICFCC. This quantity is highest for BIPFCC, followed by the BICFCC and EFCC. However, increasing TIT decreases the mass of air per mass of steam for the EFCC and BICFCC and increases this ratio for the BIPFCC (Fig. 9).

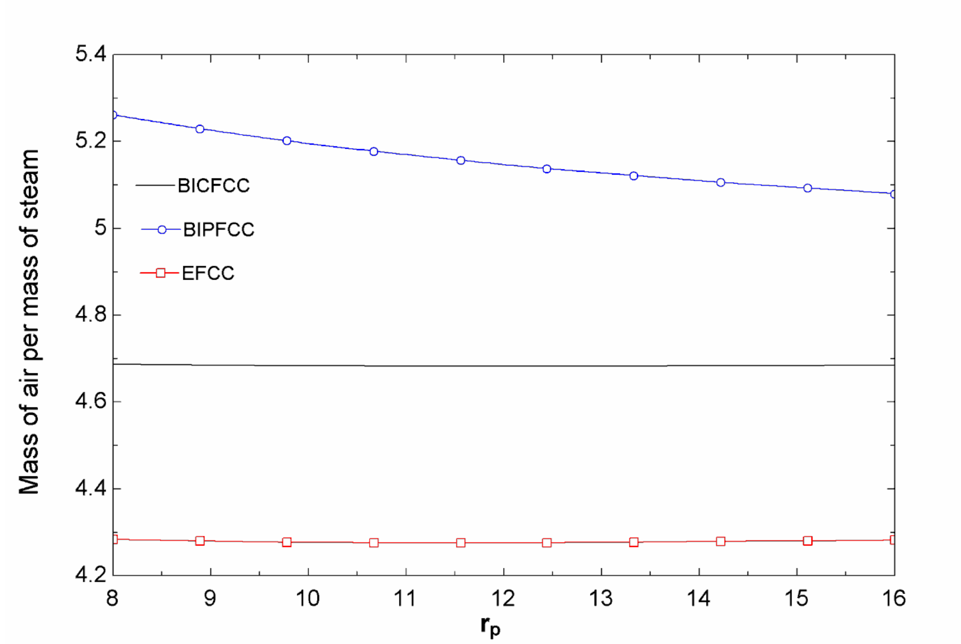

Fig. 8. Variation of mass of air per mass of steam for the cycles with r_p (TIT = 1400 K).

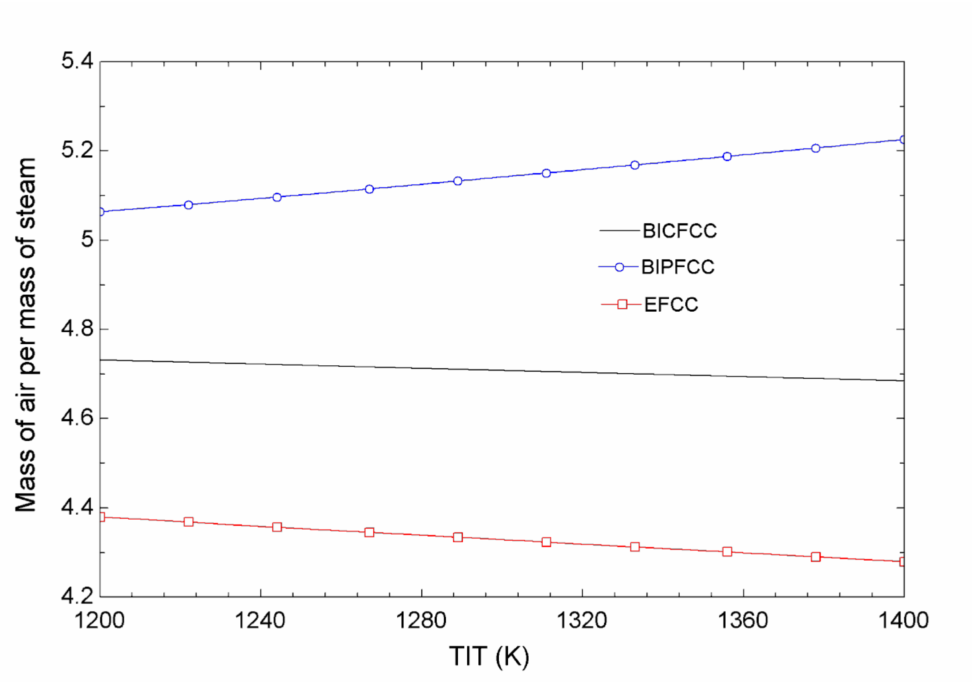

Fig. 9. Variation of mass of air per mass of steam for the cycles with TIT ($r_p = 9$).

Exergy efficiencies for the components of the three configurations are shown in Fig. 10 for the maximum energy efficiency condition. The gas turbine exergy efficiency is the highest for the three configurations, and the BIPFCC exhibits the highest gas turbine exergy efficiency. Since chemical reaction occurs in the post combustor, the combustor and the gasifier, the associated irreversibilities are high. The BICFCC combustion chamber has the highest exergy efficiency and the BIPFCC the lowest. In the post combustion chamber, the BICFCC has the highest exergy efficiency. The exergy efficiencies are the same for the three configurations for the gasifier, steam turbine, pump and HRSG, because they have the same conditions. The heat exchanger exergy efficiency is highest for EFCC. The exergy efficiency differences of the compressor, for the three configurations, are minor; the highest value is observed for the BIPFCC.

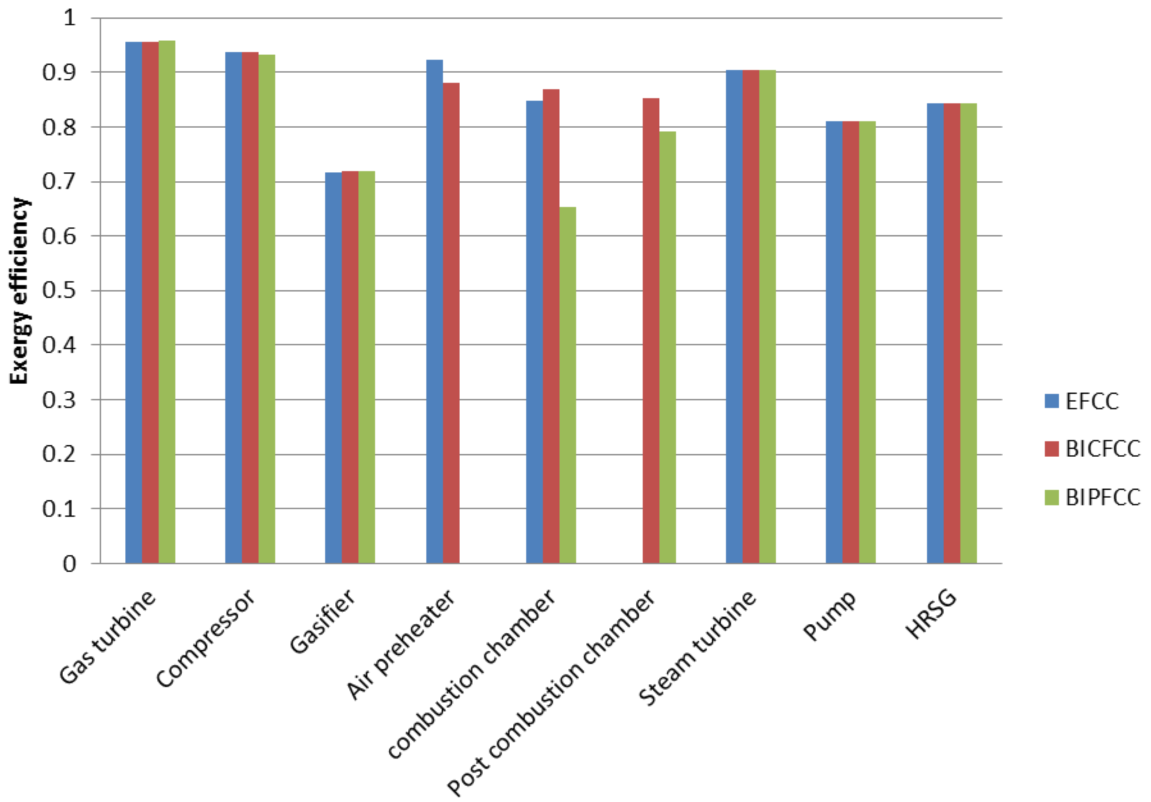

Fig. 10. Exergy efficiency of EFCC, BICFCC and BIPFCC components at maximum energy efficiency condition (TIT = 1400 K, THRSG,IN = 940 K).

5. Conclusions

Three biomass-based systems for electricity generation are successfully examined with energy and exergy analyses: externally biomass fired combined cycle, biomass integrated co-firing combined cycle and biomass integrated post-firing combined cycle. The following is concluded:

- The BIPFCC energy efficiency is about 3% and 6% points higher than those of the BICFCC and EFCC, respectively. Correspondingly, the exergy loss in BIPFCC is lower relative to the BICFCC and EFCC. The energy and exergy efficiencies of the three biomass fired configurations are maximized at particular values of compressor pressure ratio, and increasing the TIT raises the energy and exergy efficiencies for the BIPFCC, EFCC and BICFCC.

- The mass of air per mass of steam is highest for the BIPFCC, but increasing the pressure ratio reduces this value for the BIPFCC and increases it slightly for the BICFCC and EFCC. Increasing TIT raises the mass of air per mass of steam for the BIPFCC and decreases it slightly for the other cycles.

- The exergy efficiencies for the components of the three configurations, determined for the maximum energy efficiency condition, indicate that the gas turbine exergy efficiency is the highest for three configurations, the BIPFCC exhibits the highest gas turbine exergy efficiency, the BICFCC combustion chamber has the highest exergy efficiency, and the lowest exergy efficiency is for the BIPFCC. The post combustion chamber of the BICFCC exhibits the highest exergy efficiency, while the heat exchanger exergy efficiency is highest for the EFCC.

The efficiencies of biomass plants are comparatively low, but their availability, renewability and environmental characteristics can justify their use. The results may prove beneficial for designers and engineers of such systems.

Nomenclature

AP	Air pre-heater
BICFCC	Biomass integrated co-fired combined cycle
BIPFCC	Biomass integrated post-firing combined cycle
$\dot{E}$	Exergy rate (kW)
EFCC	Externally fired combined cycle
G	Gasifier
GT	Gas turbine
HRSG	Heat recovery steam generator
LHV	Lower heating value (kJ/kg)
P	Pump
P_i	Pressure at state *i*; partial pressure for species *i* (kPa)
PCC	Post combustion chamber
r_p	Pressure ratio (-)
T_i	Temperature at state *i* (K)
TIT	Gas turbine inlet temperature (K)
$\dot{W}$	Power (kW)
x	Steam quality (-)
Greek Letters	
η	Energy efficiency (-)
$\eta_{c,isen}$	Isentropic efficiency of compressor (-)
$\eta_{GT,isen}$	Isentropic efficiency of gas turbine (-)
$\eta_{ST,isen}$	Isentropic efficiency of steam turbine (-)
ε	Exergy efficiency (-)
Subscripts	
C	Compressor
CC	Combustion chamber
COND	Condenser
F	Fuel
GT	Gas turbine
in	Input

i	Index for thermodynamic state point
o	Reference environment state
P	Product
ST	Steam turbine

Conflict of Interest

"The authors declare no conflict of interest".

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