

System Performance and Pollution Emission of Biomass Gas Co-Firing in a Coal-Fired Boiler

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Abstract

To reduce greenhouse gases emission and increase the renewable energy utilization portion in the world, the biomass gasification coupled with a coal-fired boiler power generation system is studied. It is a challenge to achieve optimum performance for the coupled system. The models of biomass gasification coupled with co-firing of coal in a boiler have been established. A comparative study of three kinds of biomass (Food Rubbish, Straw and Wood Pellets) has been done. The syngas produced in a 10 t/h gasifier is fed to a 330 MWe coal-fired boiler for co-combustion, and the co-firing performances have been compared with pure coal combustion case under the conditions of constant boiler load. Results show that co-firing decreases the furnace combustion temperature and raises the flue gas temperature for Food Rubbish and Straw, while, flue gases temperature decrease in case of Wood Pellets. At the same time NO_x and SO_x emissions have reduced. The system efficiencies at constant load for Food Rubbish, Straw and Wood Pellets are 83.25%, 83.88% and 82.56% when the optimum conditions of gasification and co-firing process are guaranteed.

Keywords

Biomass Gasification, Coal-Fired Boiler, System Efficiency, Optimal Air to Biomass Ratio

1. Introduction

Nowadays energy generation is the heart of most critical, economic, environmental, and development issues of the world. Challenges are faced by the global community and national governments due to energy security, climate change, health impacts, and poverty. Shifting toward green energy production is sup-

posed to play a critical role in solving some of the most prominent contemporary challenges the world is facing at present [1]. As power demand increases, power generation increases, which results in increased emission of NO_x , SO_x and CO_2 . The largest emission source of these pollutants comes from coal-fired power plants [2]. These pollutants cause various environmentally harmful effects such as acid rain, ozone depletion and urban smog [3] [4]. Biomass gasification coupled with a coal-fired power plant is one of the solutions to the problems. In Pakistan, there produce 82 million tons of biomass. It is best to use this biomass in power generation as it reduces both fossil fuel consumption and mitigates climate change [5]. Biomass gasification is a process for converting carbonaceous material to a combustible or synthetic gas [6]. The solid biomass is converted into a gaseous product that can be handled with maximum convenience, and low cost and readily be purified to a clean fuel [7]. It is a complex process and the operational parameters in the gasification process play an important role in improving the quality and quantity of syngas [8]. As compared to the pure coal case, co-firing of syngas results in decrease of furnace combustion temperature and the increase of flue gas temperature and volume flow rate. Thus, boiler efficiency slightly decreases; however, emissions of NO_x and SO_x decline also.

Aspen Plus is a widely used process simulation software nowadays and can simulate the gasification process of biomass fluidized bed gasifier and the co-firing process of bio-gas with the coal-fired boiler. Meanwhile, the simulation results were compared with test data and the rationality of the model was verified successfully [9]. Based on chemical balance and phase equilibrium, a fixed bed gasifier model was developed using Aspen Plus. Study shows that the model can be used to predict the syngas component at optimized working conditions [10].

Biomass gasification coupled with a coal-fired power plant is more useful than directly co-firing. The co-firing of most kinds of biomass may reduce the boiler efficiency. Wet wood chip for biomass gasification was studied and gasification efficiency increased for biomass with 20% [11]. It solves boiler fouling and corrosion problems up to some extent. As biomass ash is removed before syngas is brought in a furnace, ash characteristics of the boiler remain the same [12].

In this work, the operation processes of the biomass gasification coupled with a coal-fired boiler system were simulated. Straw, Food Rubbish and Wood Pellet are employed as feedstock at gasifier. They were gasified at the air to biomass ratio varying from 0.6 to 2.4. The comparative study between three cases is done to find the best of them. The effects of the air to biomass ratio on bio-gas compositions, bio-gas low calorific value, biomass gasification efficiency, and the influences of excess air ratio on the furnace combustion temperature, flue gas compositions, boiler efficiency and the system efficiency of biomass utilization have been studied. The findings will give a reference to apply the co-firing technology in coal-fired power plants.

2. The Basic Theory of Coupled System

The operational performance of biomass gasification coupled with coal-fired

boiler directly depends upon the biomass gasification and co-firing of biomass and coal. The system includes one coal-fired boiler and one biomass gasifier. The block diagram of biomass gasification coupled with the coal-fired boiler is shown as **Figure 1**.

Three kinds of biomass are studied, which are Food Rubbish, Straw and Wood Pellets. They were gasified in a gasifier, whose capacity is constant and its mass flow rate is 10 t/h. The air is used as a gasifying agent. The cooling temperature of syngas after it leaves cooler is 450°C. Then obtained syngas from each case was entered the coal-fired boiler for co-firing with coal. Then flue gases were passed through the heating surface of the boiler. The air leakage is considered at the tail heating surface of the boiler. The boiler is a subcritical pressure and natural circulation boiler with a maximum capacity of 330 MW production. Three different co-firing cases have been studied at that of 100% Boiler Rated Load (BRL).

Fuel Analysis

The proximate analysis, Ultimate analysis and Lower heating value of the sub-bituminous coal, Food Rubbish, Straw, and Wood Pellets are shown in **Table 1**.

3. System Modeling

3.1. Biomass Gasification and Syngas Cooling Process

The biomass gasification is composed of four sequential step processes which include biomass pyrolysis, biomass gasification, separation of syngas and biomass ash and syngas cooling, as shown in **Figure 2**.

The feed biomass is gasified as a non-conventional stream. The biomass stream is passed to the DECOMP block where biomass pyrolysis is done to get conventional components such as carbon (C), sulfur (S), oxygen (O₂), hydrogen (H₂), water (H₂O), nitrogen (N₂) and ASH. Then block GASIFY is used for biomass gasification. It is used to calculate the chemical and phase equilibrium of

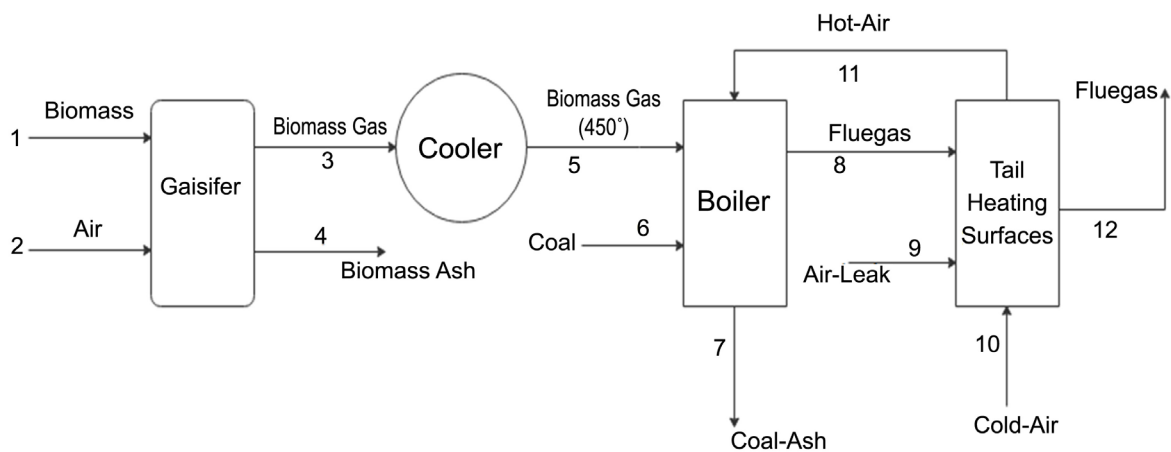


Figure 1. The block diagram of biomass gasification coupled with the coal-fired boiler system.

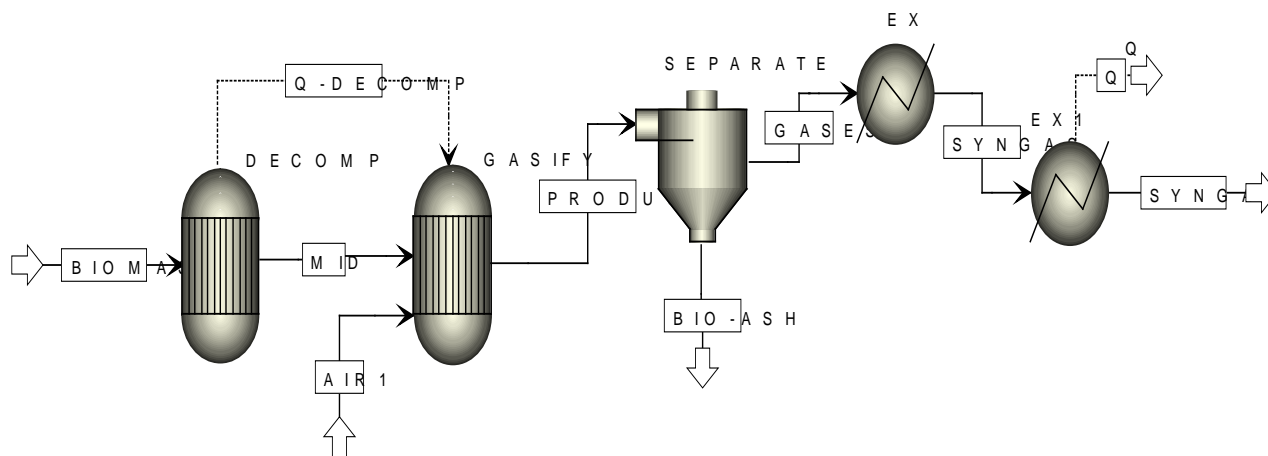


Figure 2. The simulation flow chart of biomass gasification and syngas cooling process.

Table 1. Proximate, ultimate analysis of fuel (Received basis) [13] [14].

Fuel	Proximate analysis (wt%)				Ultimate analysis (wt%)					Low calorific value/(kJ/kg)
	FC	V	A	M	C	H	O	N	S	
Sub-Bituminous Coal	25.12	41.60	7.03	26.25	48.69	4.68	11.34	1.30	0.71	19685.81
Food Rubbish	14.62	51.40	4.78	29.20	40.40	6.18	16.54	2.77	0.13	17430.90
Straw	17.75	71.45	5.93	4.87	44.55	5.33	38.46	0.74	0.12	16293.00
Wood Pellets	12.72	71.96	1.77	13.55	40.05	4.65	39.97	0.01	0.00	13675.90

the system by minimizing the Gibbs free energy. Its main purpose is to gasify solid biomass into a gas-solid stream PRODUCT. The block SEPARATE is used to separate biomass ash from syngas to get gaseous stream GASES. Then this gaseous stream enters the heat exchanger EX block where syngas is cooled to 450°C. Then this cooled stream SYNGAS, is the syngas entered into the boiler.

3.2. Co-Firing Process and Heat Exchange Process in the Tail Flue

In a co-firing process coal pyrolysis, co-firing of syngas with coal and heat exchange process in the tail are carried out. Latter this process is split into three further steps: separation of coal ash and flue gases, air leakage and heat exchange in tail flue gases channel, as shown in **Figure 3**.

Coal is pyrolyzed in the block DECOMP 1 into the products such as C, S, O₂, H₂, H₂O, N₂ and ASH. Then preheated air, syngas and coal products are co-fired in block BURN. Coal ash is separated from flue gases by the block SEP to obtain gaseous stream GAS. Then the stream GAS is introduced in the tail flue. Meanwhile, the model of the heat exchange process of tail heating surfaces of the boiler is established. It has the heat exchanger block (HEATER type) and two mixer block (MIXER type). The heat exchanger blocks HEATER is used to simulate the process in super-heater, re-heater, and economizer. The heat exchanger block PRE-FLUE and PRE-AIR are used to simulate the cooling process of the flue gases side and heating process of the air side respectively in air pre-heater.

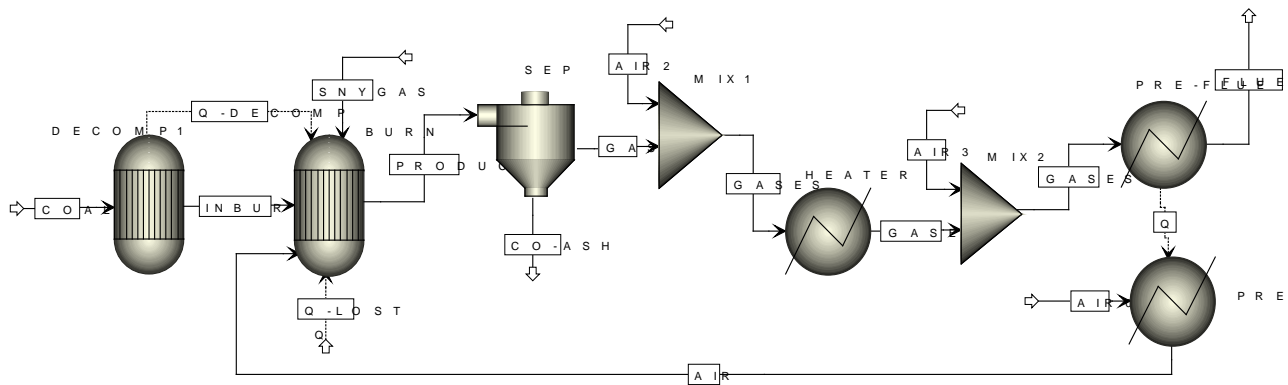


Figure 3. The simulation flow chart of co-firing and heat exchange in tail fuel.

4. Results and Discussions

4.1. Biomass Gasification Process Performance Index

The maximum heat efficiency can only be obtained at optimum air to biomass ratio. The gasification temperature at optimal air to biomass ratio of Food Rubbish, Straw and Wood Pellets is 650°C, 703°C and 652°C the syngas characteristics parameters obtained at optimum air to biomass ratio is shown in **Table 2**.

4.2. The Basic Parameters and Boiler Efficiency of the Co-Firing Process

Syngas co-firing ratio, coal consumption mass flow rate, and the theoretical air mass flow rate were obtained, as shown in **Table 3**.

As boiler load is constant, the coal consumption mass flow rate and theoretical air mass flow rate decrease in co-firing cases as compared to the pure coal case. In Food Rubbish there is a 5.06% decrease in coal consumption while 4.76% and 4.15% decrease in the case of Straw and Wood Pellets. The theoretical air mass flow rate in Food Rubbish case decreased by 1.60% while in the case of Straw and Wood Pellets it decreased 1.53% and 1.49% respectively.

4.3. Performance of the Coupled System

The highest operating efficiency of the boiler, boiler operation parameters, flue gas components and characteristics at air pre-heater outlet and system efficiency are shown in **Table 4**.

Furnace combustion temperature in pure coal case is at 1345.81°C while it decreases slightly in co-firing cases, Food Rubbish gas at 1340.87°C, Straw gas at 1342.83°C, and Wood Pellets gas at 1340.23°C. Flue gas temperature increases in the case of Food Rubbish gas and Straw gas co-firing but decreases in the case of Wood Pellets gas co-firing, as compared to pure coal case. There are slight oscillations in the flue gases flow rate. Boiler efficiency slightly decreases in co-firing cases. The volume fraction of the main components of flue gases H₂O and CO₂ increases while N₂ and O₂ decreases in co-firing cases. The volume fraction of pollutant components nitrogen oxide (NO), nitrous oxide (N₂O), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and sulfur trioxide (SO₃) decreases.

Table 2. Optimal syngas components and gasification characteristic parameters.

Item		Food Rubbish	Straw	Wood Pellets
Main components volume fraction/%	H ₂ O	7.85	4.23	7.04
	N ₂	40.70	40.32	36.64
	H ₂	25.75	21.52	22.26
	CO	15.00	25.49	20.07
	CO ₂	9.48	7.99	12.90
	CH ₄	1.22	0.45	1.09
Gasification temperature/°C		649.72	702.94	651.79
Lower heating value/(kJ/Nm ³)		5110.07	5695.81	5321.46
Sensible heat/(kJ/kg)		2307.99	1726.22	2385.51
Gasification efficiency/%		79.18	82.40	79.08
Gasification heat efficiency/%		92.42	93.00	91.55

Table 3. Mass flow rate of coal consumption and theoretical air mass.

Item	Pure coal (sub-bituminous coal)	Food Rubbish	Straw	Wood Pellets
Co-firing ratio (%)	—	5.06	4.76	4.15
Coal consumption mass flow rate (kg/h)	163004.26	154748.35	155239.14	156239.28
Theoretical air mass flowrate (kg/h)	1259999.06	1239716.78	1240603.77	1241205.63

Table 4. Flue gas components, flue gases characteristic and coupled system performance.

Item		Pure coal (sub-bituminous coal)	Food Rubbish	Straw	Wood Pellets
Furnace combustion temperature/°C		1345.81	1340.87	1342.83	1340.23
Main components volume fraction/%	H ₂ O	10.52	10.95	10.75	10.85
	N ₂	72.80	72.23	72.32	72.22
	O ₂	5.30	5.28	5.32	5.32
	CO ₂	11.38	11.54	11.61	11.61
	NO	1.07E+01	5.94E-02	6.03E-02	5.95E-02
Pollutant components volume fraction/%	N ₂ O	3.12E-06	3.00E-06	3.04E-06	3.00E-06
	NO ₂	7.71E-05	7.37E-05	7.49E-05	7.44E-05
	SO ₂	6.23E-02	5.98E-02	6.00E-02	5.98E-02
	SO ₃	2.07E-04	1.99E-04	2.00E-04	2.01E-04
Flue gases temperature (°C)		160.30	163.04	161.74	158.83
Flue gases mass flow rate (kg/h)		1,670,431	1,670,985	1,669,224	1668139.9
Gasification efficiency %		-	79.18	82.40	79.08
Boiler efficiency (%)		90.20	90.08	90.19	90.18
System efficiency (%)		-	83.25	83.88	82.56

The reason behind the reduction of NO_x and SO_x in flue gas is that the presence of reductive gases carbon monoxide (CO), H_2 , and methane (CH_4) in syngas. It reduces NO_x to N_2 along with the generation of H_2O and CO_2 under reducing temperature. That is why the H_2O and CO_2 content increase in flue gases after co-firing. The decrease in combustion temperature and the presence of N and S in biomass fuel is the most important factor in the reduction of volume fraction of NO_x and SO_x [15] [16] [17] [18].

System efficiency is 83.25% in the case of Food Rubbish gas co-firing, 83.88% in the case of Straw gas and 82.56% in Wood Pellets gas case.

5. Conclusion

A 330 MWe boiler and a 10 t/h gasifier are employed to simulate the co-firing system performance and pollution emissions. It found the syngas from straw had maximum boiler efficiency as compared to that of Food Rubbish and Wood Pellets in co-firing cases, and the co-firing of straw syngas had a maximum system efficiency of 83.88% while Food Rubbish and Wood Pellets were 83.25% and 82.56% respectively. As compared to pure coal case it is observed that in co-firing cases the furnace combustion temperature decreased and the flue gases temperature increased, but in case of Wood Pellets the flue gases temperature decreased. The volume flow rate also increased in the case of Food Rubbish and Straw but decreased in the case of Wood Pellets. Boiler efficiency and emission of NO and SO_2 reduced in the case of co-firing.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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