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Thermodynamic Comparison of alternative Biomass Gasification Techniques for producing Syngas for Gas Turbine Application

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Abstract

In this paper, Aspen Plus® models of biomass gasification process combined with plasma reactor for tar removal and plasma gasification process were developed respectively, validated and analyzed thermodynamically. The analysis shows that plasma technology is capable of producing syngas with acceptable tar content for gas turbine application. However, this comes with a huge energy penalty. For example, within the context of the analysis carried out in this paper, the thermodynamic efficiency of the biomass gasification process combined with plasma tar cleaning was found to be 43.6% while that of the plasma gasification process was 37.3% despite its higher bio-syngas calorific value. The lower efficiency recorded for the plasma gasification process occurs as a result of the higher electrical energy required to attain the high temperature needed for the gasification of the biomass material. As a result of the low efficiency, plasma tar cleaning of raw bio-syngas or plasma gasification, although technologically feasible, may not be a viable route for producing bio-syngas for gas turbine application. However, it may be a viable option for energy storage if the plasma reactor will be powered with electricity from wind and other renewable energy resources during off peak period.

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Keywords: Biomass; Gasfication; Plasma; Tar removal; Process Simulation; Thermodynamic analysis

1. Introduction

The growing concern on safeguarding the environment from the harmful effect of global warming caused by the release of large quantities of CO_2 into the environment; mainly from fossil fuels utilization for energy production;

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has triggered a renewed interest in the use of renewable energy resources. One of the areas in which biomass can help to reduce CO_2 emission into the environment is in gas turbine application by replacing natural gas with bio-syngas.

1.1. Bio-syngas Production from Biomass

Bio-syngas is produced from biomass through the thermochemical conversion route. During the process, thermal energy is applied to biomass material at elevated temperature and controlled oxygen and/or steam to produce permanent gases, char and tars. The process involves three main stages which include: drying, pyrolysis and gasification [1]. During the drying stage the free water contained in the biomass is evaporated. This is followed by a pyrolysis which occurs at around 400 ^{o}C to release pyrolytic volatiles, pyrolytic water (chemically bond water), char and primary tar which consist of mainly oxygenated compounds. The pyrolytic water, primary tar and moisture are generally referred to as the bio-oil. The pyrolysis products are further gasified to produce raw bio-syngas otherwise known as product gas or permanent gas. The gasification process occurs at a higher temperature (about 700 – 850 ^{o}C) and is mainly characterized by further cracking of pyrolysis (primary) tar in order to produce permanent gases (raw bio-syngas) as well as secondary and tertiary tar compounds [2]. Alternatively, syngas can be produced from biomass material using plasma gasification technology. In this process, plasma is used to decompose the biomass material to produce syngas.

1.2. Raw Bio-syngas Tar Cleaning

Tar is a term generally used to describe a complex mixture of condensable hydrocarbons which includes single ring to multiple ring aromatics and other oxygen containing hydrocarbons [3]. It is an undesirable component in the bio-syngas due to the problems associated with its condensation as it causes blockage in process equipment and devices [3]. Gas turbines have a maximum tar tolerance of no more than 0.5 mg/Nm^3. However, raw bio-syngas usually contain high tar concentration which makes it unsuitable for gas turbine and other high end applications without prior tar removal. Tar removal is carried out by either chemical or physical treatment. Detailed research on the different tar cleaning techniques are well covered in the literature [5-8,9, 10] and thus will not be repeated here. This work will focus on the use of plasma technology for tar removal from bio-syngas.

Plasma technology can generate active species which initiates the chemical reactions that can lead to tar reduction. There are many discussions, especially in the patent literature, on the possibilities of using both thermal and non-thermal plasma technology for waste gasification, dry reforming and tar reduction from gasifier [11-13]. This paper will compare via modelling; the thermodynamic performance of biomass gasification process combined with ex-situ plasma tar cleaning against that of a plasma gasification process. The modelling will be carried out using Aspen Plus coupled with FORTRAN subroutines.

1.4 Novel contribution of this study

Although several studies have been carried out in literature, both experimental and modelling, in the area of biomass gasification and plasma reforming of various gaseous species such as methane, ethylene, naphthalene, to the authors knowledge, no work has been reported in the literature on the integration of plasma reactor downstream of a biomass gasification process for tar removal from the raw bio-syngas stream for gas turbine application. Furthermore, most works on plasma uses a model tar compound in their analysis instead of a real syngas composition from biomass gasification process. However, in this paper, the thermodynamic analysis was based on a typical bio-syngas composition instead of a model tar compound which makes it a more realistic.

2. Process Description

2.1. Biomass gasification process

The biomass gasification technology adopted in this paper is based on the technology proposed in [14, 15]. The process comprises of dual fluidized bed reactor which utilises steam as the gasification agent. During the process, biomass is gasified in a steam blown bubbling fluidised bed reactor. Residual char leaves the gasification zone with the bed material (usually sand) and enters the circulating fluidised bed riser where it is combusted with air [15].

2.3 Plasma gasification and Plasma Tar Cleaning process

The plasma gasification process presented in this work is based on the non-transferred arc DC plasma torch technology proposed in [16]. The pulse corona plasma reactor modelled in this paper is based on the experimental work carried out in [3]. The system consists of a cylindrical tubular flow reactor which is a wire-cylinder type corona and a pulsed-power source.

3. System Modeling with Aspen Plus

The Aspen Plus® process flow diagram of the proposed biomass gasification combined with ex-situ plasma tar cleaning process and the plasma gasification process are shown in Figures 1a and 1b. The biomass gasification process is modelled using detailed kinetic mechanism [14] while the plasma gasification and plasma tar cleaning processes are modelled using complete equilibrium approach [17]. In the process, the biomass material (stream 1) undergoes pyrolysis in an isothermal reactor (PYROLY) which is coupled to a FORTRAN subroutine to predict the pyrolysis product yield (stream 2) based on pyrolysis correlation given in [14]. The pyrolysis yield (stream 2) is then mixed with steam (stream S1) (the gasifying agent) and introduced into the gasifier (GASIFY (process a) or HTZPLAS (process b)) where gasification takes place according to either the gasification kinetics presented in [14] (process a) or chemical equilibrium (process b) to produce gasification products (stream 4). The solid products are separated from the volatiles in the SPLITTER. In process a, the volatiles (stream 5) are sent to the plasma reactor (PLASMA) where tar cleaning operation takes place to produce low tar syngas (stream 7) while in process b, the high temperature syngas from the High Temperature Zone (HTZ) of the gasifier is quenched at Low Temperature Zone (LTZ) by preheating the incoming biomass feed. In both cases, the char is decomposed and combusted with air to produce flue gas (stream 10) and ash (stream 11) respectively. The following assumptions were made while modelling the biomass gasification in Aspen Plus [3].

- In process a, gasification and the plasma processes take place at atmospheric pressure and 760 ^oC
- In process b, the HTZ and the LTZ are assumed to be at 2500 ^oC and 1250 ^oC respectively [16].
- The main components of the pyrolysis products include CO, H_2, CO_2, CH_4, C_2H_4, C_2H_6, water and tar.
- The plasma process is modelled using Gibbs minimization approach [16]
- As naphthalene is regarded as one of the most stable tar compounds [3], the empirical correlation for tar conversion used in this model is based on naphthalene conversion in a pulsed corona discharge.
- Steam is used as the gasifying agent with steam to biomass ratio of 0.75 [15]
- The steam is assumed to be generated from saturated liquid water removed from the raw bio-syngas.
- In the plasma gasification process, the steam from the plasma torch is assumed to be at 4000 ^oC [16]
- The plasma torch efficiency for the plasma gasification process is assumed to be 86% [16]

3.1. Pyrolysis and Gasification Process

For both processes, the pyrolysis volatile mass yield is modelled using equation 1 [3] while the char yield is obtained through material balance. The correlation parameters (*a*, *b* and *c*) in equation 1 were obtained from [14]. The thermal gasification process was modelled using the reaction kinetics obtained from [14] while the plasma gasification process was modelled using Gibbs equilibrium technique. Tables 1 shows the input parameters used in the entire model.

$$Y_i = aT^2 + bT + c \quad (1)$$

where Y_i = mass yield of pyrolysis product based on dry biomass, T = pyrolysis temperature in K

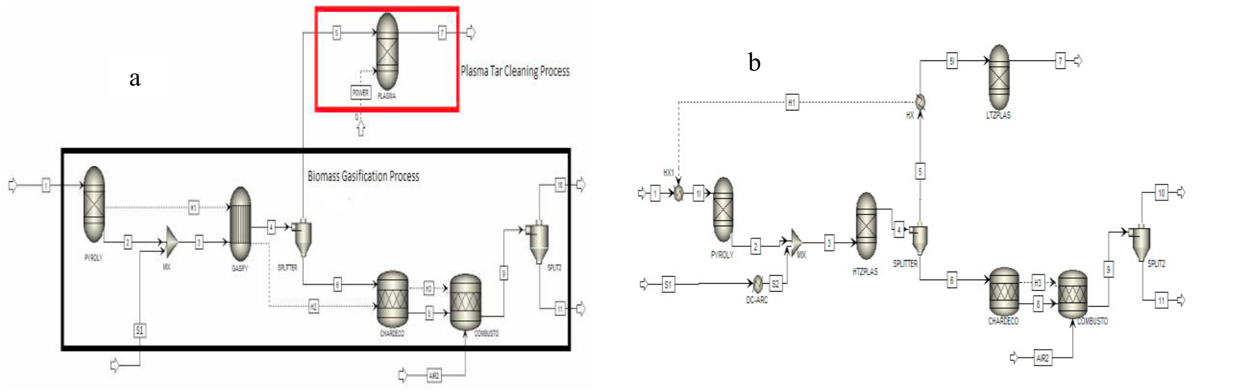

Fig. 1. Aspen Plus Process Flow Diagram of (a) Biomass Gasification combined with Ex-Situ Plasma Tar Cleaning and (b) Biomass Plasma Gasification

Table 1: Process input parameters

Biomass Composition and Plasma Tar Cleaning Process			
Gasification Process			
Biomass mass flowrate		1 kg/s	
Proximate analysis (wt% dry basis)		Ultimate analysis (wt% dry basis)	
Volatile matter	83.70	Carbon	53.60
Fixed carbon	16.10	Hydrogen	5.90
Ash	0.20	Oxygen	40.30
Pulse Corona Plasma Process			
Input stream		Raw bio-syngas	

3.2. Pulse Corona Plasma Process

The pulse corona process was modelled using empirical correlation generated from the experimental work of [3] together with the Gibbs free energy minimization approach presented in [16]. The correlation was used to evaluate the tar conversion based on the energy density of the pulse corona while the Gibbs reactor is used to simulate the equilibrium composition of gaseous species from the plasma reactor. The correlation for the tar conversion is shown in equation 2.

$$x(\%) = -9.53\times10^{-15}\beta^{6} + 1.85\times10^{-11}\beta^{5} - 1.33\times10^{-8}\beta^{4} + 4.71\times10^{-6}\beta^{3}$$

$$-1.266\times10^{-3}\beta^{2} + 4.56\times10^{-1}\beta + 1.56 \quad (2)$$

where $x(\%)$ = tar conversion, β = Energy density (J/l) of the plasma reactor given as shown in equation 3

$$\beta = \frac{P}{v} \quad (3)$$

where P = power input to the reactor (W) and v = volumetric flowrate of the raw bio-syngas.

The syngas produced during the gasification process (raw bio-syngas) and the one obtained after the tar removal with plasma (treated bio-syngas) were evaluated to estimate the tar content using the ideal gas equation while the specific calorific value (cv) (MJ/kg) of the biomass and bio-syngas were evaluated using equations 4 and 5 respectively.

$$CV_{biomass} = 33.83C + 144.45\left(H - \frac{O}{S}\right) + 9.38S \quad (4)$$

where $C, H, O, S =$ mass fraction of carbon, hydrogen, oxygen and sulphur in the biomass

$$CV_{syngas} = \sum_i m_i HV_i \quad (5)$$

where m_i and HV_i = mass flowrate of combustible gas components in the syngas (kg/s) and specific heating value of the combustible gas components respectively

4. Results and Discussions

The analyses of the simulation results show that the tar content of the raw bio-syngas from the biomass gasification process was about 2.97 mg/Nm^3 which makes it unsuitable for gas turbine application. The plasma tar cleaning reduces the tar content of the raw bio-syngas to 0.266 mg/Nm^3 which is within the acceptable range (<0.5 mg/Nm3) for gas turbines. Plasma treatment of the raw bio-syngas also improved the caloric value of the syngas due to the increase in hydrogen and CO yield. The thermodynamic analysis presented in Table 3 shows that the efficiency of the combined plasma gasification with plasma tar cleaning process is about 43.6 %. On the other hand, the plasma gasification process produces syngas with higher calorific value due to the higher hydrogen and CO and no tar (see Table 2). This ocurs as a result of the high temperature of the HTZ and LTZ of the plasma gasification process. However, despite the improvement in syngas caloric value, the thermodynamic efficiency of the plasma gasification process was found to be 37.3% which is lower than that of the combined gasification and plasma tar cleaning process. The lower efficiency can be attributed to the higher electrical energy required for the plasma gasification process to raise the temperature of the gasifying agent (steam) to 4000 ^oC so as to maintain the HTZ and the LTZ of the non-transferred arc plasma reactor at 2500 ^oC and 1250 ^oC respectively.

Table 2: Raw/Treated Bio-syngas composition (mole fraction dry basis)

Component	Raw bio-syngas (760 ^oC)	Plasma treated bio-syngas (760 ^oC)	Plasma Gasification (1250 ^oC)
CH_4	0.206	3.07E-5	1.07E-8
H_2	0.127	0.6270	0.5912
CO	0.518	0.0922	2.07E-1
CO_2	0.093	0.281	2.01E-1
C_2H_4	0.049	9.70E-13	4.81E-16
C_2H_6	0.005	3.62E-13	7.42E-19
$^aC_6H_6$	0.001	2.52E-5	0
$^aC_7H_8$	1.38E-4	4.73E-6	0
$^aC_6H_6O$	0	0	0
$^aC_{10}H_8$	1.91E-5	6.56E-7	0

a = Tar

Table 3: Thermodynamic analysis

Process results	Plasma treatment at 760 ^oC	Plasma Gasification at 1250 ^oC
Treated syngas calorific value (MW)	9.857	10.929
Thermal energy requirement for steam generation (MW)	1.693	0
Electrical power requirement (MW)	1.526	9.927
Biomass calorific value (MW)	19.38	19.38
Total energy input (MW)	22.599	29.307
Process efficiency η	0.436	0.373

Conclusion

The thermodynamic analysis of biomass gasification process combined with tar removal using plasma technology and the plasma gasification process presented in this paper shows that plasma technology is capable of producing bio-syngas with acceptable tar concentration for gas turbine application. However, this comes with a huge energy penalty. Based on the analysis presented in this work, it can be concluded that plasma tar cleaning of raw bio-syngas and plasma gasification, although technologically feasible, may not be an attractive option for tar removal from raw bio-syngas especially if the syngas is to be utilized in gas turbines for power generation. However, it may be an attractive option for the storage of wind and other renewable electricity during off peak period.

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