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Energy and exergy analysis of biomass gasification at different temperatures

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ABSTRACT

Biomass is usually gasified above the optimal temperature at the carbon-boundary point, due to the use of different types of gasifiers, gasifying media, clinkering/slagging of bed material, tar cracking, etc. This paper is focused on air gasification of biomass with different moisture at different gasification temperatures. A chemical equilibrium model is developed and analyses are carried out at pressures of 1 and 10 bar with the typical biomass feed represented by $CH_{1.4}O_{0.59}N_{0.0017}$. At the temperature range 900–1373 K, the increase of moisture in biomass leads to the decrease of efficiencies for the examined processes. The moisture content of biomass may be designated as “optimal” only if the gasification temperature is equal to the carbon-boundary temperature for biomass with that specific moisture content. Compared with the efficiencies based on chemical energy and exergy, biomass feedstock drying with the product gas sensible heat is less beneficial for the efficiency based on total exergy. The gasification process at a given gasification temperature can be improved by the use of dry biomass and by the carbon-boundary temperature approaching the required temperature with the change of gasification pressure or with the addition of heat in the process.

1. Introduction

Biomass is regarded as a type of renewable energy since the carbon dioxide emissions, resulting from the use of biomass as a fuel, are fixed by photosynthesis later on. There are global incentives for the use of biomass. The most important is the Kyoto protocol [1].

A promising way to use biomass for production of heat, electricity, and other biofuels is through biomass gasification. It is a thermo-chemical process of gaseous fuel production by partial oxidation of a solid fuel. In this process, the chemical energy of the solid fuel is converted into the chemical and thermal energy of the product gas.

The aim of this paper is to determine what are the benefits of feedstock drying with the product gas sensible heat, whether an optimal moisture content exists at a given gasification temperature, and how the efficiency at a given gasification temperature can be improved. Gasification temperature and its uniformity depend on the gasification technology employed (fixed bed, fluidized bed, entrained bed gasifiers), the gasifying medium used (oxygen and/or hydrogen source), the characteristics of biomass (moisture and ash contents, volatile compounds, particle size), in particular the softening and melting temperatures of the ash, the characteristics of bed material (in order to avoid its slagging/clinkering), and the tar cracking process applied (catalytic or thermal).

The work of Ptasinski et al. [2] is the basis for this paper. In that work gasification of various biofuels was analyzed at the so-called carbon boundary point (CBP). The CBP is obtained when exactly enough gasifying medium is added to avoid carbon formation and achieve complete gasification. Desrosiers [3], Double and Bridgwater [4] proved that the CBP is the optimum point for gasification with respect to energy-based efficiency, and Prins et al. [5] proved that it is the optimum point with respect to exergy-based efficiency, as cited by Ptasinski et al. [2]. It was also concluded in [2] that gasification of sludge and manure is not possible at the optimum point, because these fuels contain large amounts of moisture so that the carbon boundary temperature is lower than 600 °C. To gasify these fuels, the use of the product gas sensible heat for drying of biomass (in the absence of an alternative, external source of heat) was recommended.

This paper also aims to resolve how the external addition of heat influences the optimal gasification conditions of biomass with different moisture. The allothermal gasification processes obtain all or part of the heat necessary for endothermic gasification reactions by the use of sun energy [6], electrical energy in plasma gasification [7], and by the addition of heat into gasifiers. Gasifiers presented in

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Nomenclature

c_c	molar specific heat capacity of solid carbon, kJ/(kmol K)
c_p	molar specific heat capacity at constant pressure, kJ/(kmol K)
Cc	calorific value of carbon, kJ/kg
char	weigh fraction of unconverted carbon, wt%
Cs	calorific value of sulfur, kJ/kg
D	number of data
e	specific molar exergy, kJ/kmol
$e_{ch,biomass}$	chemical exergy of biomass, kJ/kg
E	energy, kJ
ER	equivalence ratio, -
g	molar specific Gibbs function, kJ/kmol
g_f^o	molar specific Gibbs function of formation at the SRS, kJ/kmol
h	molar specific enthalpy, kJ/kmol
h_{fg}	enthalpy of evaporation for water, 44011 kJ/kmol at 298 K
HHV_{fuel}	higher heating value of fuel, MJ/kg
$LHV_{biomass}$	lower heating value of biomass, kJ/kg
LHV_{gas}	lower heating value of product gas, kJ/kmol
LHV_{org}	lower heating value of the organic fraction of biomass, kJ/kg
m	kmol of oxygen per kmol of feedstock
M	molar mass, kg/kmol
Mod	predicted value from model
n_{air}	molar amount of air, kmol
n_C	molar amount of carbon in biomass, kmol
n_{gas}	molar amount of product gas, kmol
n_H	molar amount of hydrogen in biomass, kmol
n_{H_2O}	molar amount of water vapor used for gasification, kmol
n_N	molar amount of nitrogen in biomass, kmol
n_o	molar amount of oxygen in biomass, kmol
OR	the value taken from other researchers
p	pressure, Pa
p_o	pressure at the SRS, 0.1 MPa
Q	heat gain of loss, $kJ/kg_{biomass}$
R	universal gas constant, 8.314472 kJ/(kmol K)
RMS	root-mean-square
S	molar specific entropy, kJ/(kmol K)
$S^{O}_{T_o}$	molar specific absolute entropy at the SRS, kJ/(kmol K)
T	temperature, K
T_o	temperature at the SRS, 298 K
x	molar fraction, mol%
x_{O_2air}	molar fraction of oxygen in air, 0.21 mol%
x_{N_2air}	molar fraction of nitrogen in air, 0.79 mol%
y	experimentally determined mass fraction of gas stream 1
Z_A	weight fraction of ash, wt%
Z_C	weight fraction of carbon, wt%
Z_H	weight fraction of hydrogen, wt%
$Z_{\mathbf{N}}$	weight fraction of nitrogen, wt%
Z_O	weight fraction of oxygen, wt%
Z_{org}	weight fraction of organic fraction in biomass, wt%
Z_W	weight fraction of moisture, wt%
Z_S	weight fraction of sulfur, wt%

Abbreviations

CBP	carbon boundary point
HHV	higher heating value
LHV	lower heating value
SRS	standard reference state

Superscripts

*	reference state of 0.1 MPa and temperature T

Subscripts

air	air used for gasification
C	carbon
ch	chemical
gas	product gas
i, j, k	i, j, k th species
org	organic matter
p	preheating
ph	physical
S	sulfur
T	at temperature T(K)
T_O	at temperature 298 K
1	the gas obtained in the first part of the model
2	the gas obtained by the equilibrium model
3	gas stream used in modified model
1,2	conditions at the entrance and at the exit of a drier, respectively

Greek letters

β	ratio of the chemical exergy and the LHV of dry organic substances, -
Δh	enthalpy difference at any given T and at 298 K, kJ/kmol
n	chemical efficiency, %
Ψ	exergy efficiency, %

[8,9] use steam as the medium and obtain the heat for endothermic gasification reactions by the heated bed material that is fed into the gasifiers. In addition, there are processes that use heat fluxes for endothermic gasification reactions like in an indirectly heated pyrolyser in the Viking gasification concept [10] or in the so-called Biomass Heatpipe Reformer [11] where the liquid metal heatpipes are used to create high heat fluxes from a combustion chamber to the gasifier. Maréchal [12] thermodynamically analyzed the Fast Internally Circulating Fluidised Bed [9] and the Viking gasification concepts [10], and Hamel et al. [8] presented multi-stage gasification processes that use the heat produced outside the gasifiers for endothermic reactions.

For the purpose of the present analysis, a two-stage chemical equilibrium model that uses mass and energy balances is developed and validated. The model enables determination of the CBP and analysis of gasification below and above this point.

The biofuel used in the analysis is a typical dry, ash-free biomass represented by the general formula $CH_{1.4}O_{0.59}N_{0.0017}$ that was also used in [3,5]. The moisture content in the biomass is varied in the range from 0 wt% to 30 wt%. This upper limit can be obtained by air-drying of biomass, and is taken because the larger moisture contents make ignition difficult and reduce the heating value of the gas [13]. The effect of pressure is studied at 0.1 MPa and at an elevated pressure of 1 MPa. The gasifying medium in all analyses is the combustion air at 25 °C consisting of 21 mol% oxygen and 79 mol% nitrogen.

At higher gasification temperatures, the sensible heat has a significant portion in the total energy of the product gas. If the