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Assessment of syngas composition variability in a pilot-scale downdraft biomass gasifier by an extended equilibrium model

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HIGHLIGHTS

- Direct influence of devolatilization products on syngas composition.
- Clear correlations among chemical species in the syngas.
- An important relationship between the methane and ethylene content.
- Devolatilization products in the syngas linked to bed channeling.

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ABSTRACT

A new simplified approach based on equilibrium modeling is proposed in this work to describe the correlations among syngas species experimentally observed in a pilot scale downdraft biomass gasifier operated with different feedstocks (biomass pellets and vine prunings). The modeling approach is based on experimental evidence on the presence of devolatilization products in the syngas and fluctuations of syngas composition during stationary operation, accounted for by introducing two empirical parameters, a by-pass index and a permeability index. The simplified model correctly reproduces the correlations among the main syngas species (including methane and ethylene) resulting from experimental data of pilot tests with different feedstocks and under a wide range of operating conditions.

1. Introduction

The prediction of the composition of the syngas produced by biomass gasifiers is an important part in the development of modeling tools, which can support the understanding of the gasifier phenomenology as well as the assessment of the gasification performance.

This task requires an accurate representation of several phenomena involved in a gasification system, such as devolatilization, heterogeneous and homogeneous reactions, heat and mass transfer. In most cases, the development of complex models may result inapplicable, due to the lack of information and data needed to run the simulations.

As far as fixed bed gasifiers are concerned, a simple approach to compute the syngas composition relies on equilibrium models (Zainal et al., 2002; Altafini et al., 2003; Jarungthammachote and Dutta, 2007; Balu and Chung, 2012; Barman et al., 2012). These models often consider a stoichiometric combustion of the biomass in the oxidation zone followed by an equilibrium stage. As observed by Balu and Chung (2012) these models often underestimate the methane content in the syngas and to this purpose Barman et al. (2012) introduced a deviation from the equilibrium in the methane formation reaction to fit its prediction with the experimental values.

Equilibrium models cannot account for the presence of ethylene in the syngas. Although its concentration is usually low compared to other major species, ethylene is usually more abundant than other hydrocarbons (Wander et al., 2004; Simone et al., 2012a) and it is considered an indicator of biomass devolatilization (Boroson et al., 1989; Fagbemi et al., 2001).

Model predictions are usually compared with average syngas composition, which is clearly satisfactory when the model is used to evaluate gasification performance. However, experimental tests at pilot scale (Simone et al., 2012a,b) show that the syngas composition is characterized by a dynamic evolution, affected by operating parameters and bed properties.

To be reliable, a simplified gasification model should take into account at least the variation of the syngas composition and be able to describe the presence of the most important hydrocarbons in the syngas.

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Nomenclature

α_i	devolatilization yield of the ith component (–)
b	by-pass index (–)
c_{ij}	stoichiometric combustion coefficient of the ith component in reaction j (–)
C_{pi}	specific heat of ith component (J mol^{-1} K^{-1})
δ	heat loss coefficient (–)
g_{ij}	stoichiometric gasification coefficient of the ith component in reaction j (–)
Δh_{cj}	enthalpy of reaction cj
m_{bio}	biomass loading rate (kg h^{-1})
n_i^{devo}	ith component molar flux after drying and devolatilization (kmol h^{-1})
n_i^{oxi}	ith component molar flux from the oxidation zone (kmol h^{-1})
n_i^{red}	ith component molar flux from the reduction zone (kmol h^{-1})
$n_i^{by\text{-}pass}$	ith component molar flux from the by-pass (kmol h^{-1})
P_0	atmospheric pressure (mm H_2O)
P_j	pressure in the annular jacket (mm H_2O)
P_n	pressure at the nozzle outlet (mm H_2O)
ΔP_j	pressure difference between the atmosphere and the annular jacket of the gasifier (mm H_2O)
ΔP_n	pressure difference between the atmosphere and the nozzle outlet of the gasifier (mm H_2O)
PM_i	molecular weight of ith component (g mol^{-1})
R_{cj}	combustion reaction rate (kmol h^{-1})
R_{gj}	gasification reaction rate (kmol h^{-1})
r_{tj}	tar cracking and hydrocarbon reforming reaction rate (kmol m^{-3} h^{-1})
t_{ij}	stoichiometric tar cracking and hydrocarbon reforming coefficient of the ith component in reaction tj (–)
T^{devo}	devolatilization zone temperature (K)
T^{oxi}	oxidation zone temperature (K)
$V^{by\text{-}pass}$	by-pass volume in the oxidation zone (m^3)
x_{moi}	biomass moisture content (–)
X	permeability index (–)

In this work a new simplified approach based on equilibrium modeling is proposed which reproduces the variation of the syngas composition observed in a pilot scale downdraft gasifier operated with different feedstock.

2. Methods

2.1. Experimental setup

The experimental tests are carried out with a pilot scale downdraft biomass gasifier (described in detail in Simone et al. (2012a)). The plant is operated slightly below atmospheric conditions due to a fan-blower positioned at the end of the gas clean-up line, which drives air to enter the gasifier through four nozzles positioned in the throated section of the gasifier. This oxygen rich section is called oxidation zone, since combustion reactions occur there. The section above the oxidation zone is oxygen-free but in the proximity of the oxidation zone the temperature is sufficiently high for biomass drying and devolatilization to take place. Heterogeneous gasification reactions occur in the section below the throat, called reduction zone.

The produced syngas moves upward from the bottom of the gasifier in an external annular jacket and enters the clean-up system where the syngas is scrubbed with water and filtered before being analyzed.

The gasification plant is equipped with two on-line instruments for gas sampling and analysis: a micro-gas chromatograph (micro-GC) and a Fourier Transform Infra-Red Spectrometer (FTIR).

The micro-GC (Agilent 3000) allows analyzing hydrogen, light hydrocarbons and permanent gases in around 4 min. The micro-GC is equipped with two independent channels based on an injector, a column and a thermal-conductivity detector (TCD). The first channel is based on a Molsieve 5A column, using argon as mobile phase and is suitable for the separation of hydrogen, oxygen, nitrogen, methane and carbon monoxide. The second channel is based on a PLOT U column using helium as mobile phase and suitable for the separation of carbon dioxide, ethane, ethylene and acetylene. The micro-GC is equipped with a pump for gas sampling and a membrane filter.

FTIR measurements are performed using a Bruker Tensor 37 FTIR spectrometer, installed in a specifically developed pressurized cabinet. The apparatus is equipped with a pump for gas sampling including valves and manometers for pressure control and a heated transfer line. A heated gas cell (stainless steel body, 10 cm optical pathlength, 25 ml volume, 200 °C maximum temperature) is used for gas analysis.

Both the analyzers are connected to the plant after the syngas clean-up, consequently the gas at the sampling point is free of water vapor and the compositions are referred to the dry syngas.

The gasifier behavior during operation is monitored using a permeability index, defined as:

$$X = \frac{\Delta P_n}{\Delta P_j}$$

where:

- ΔP_j is the pressure difference between the atmospheric pressure (P_0) and the pressure in the annular jacket of the gasifier (P_j):

$$\Delta P_j = P_0 - P_j$$

- ΔP_n is the pressure difference between the atmospheric pressure (P_0) and the pressure at the nozzle outlet inside the gasifier (P_n):

$$\Delta P_n = P_0 - P_n$$

The permeability index displays a remarkable influence on the gasifier operation, affecting the syngas productivity and operative stability (Simone et al., 2012a). In particular, air adduction and syngas flow-rate increases with the bed permeability.

2.2. Descriptive approach

Several experimental tests with the pilot scale downdraft biomass gasifier were performed using different types of biomass as feedstock (Simone et al., 2012a,b). In particular, seven tests are considered for the analysis performed in this paper. Wood pellets were used in Test 1, Test 2 and Test 3; a mix of wood pellets and sunflower cake pellets was used in Test 4 and Test 5; vine prunings were used in Test 6 and Test 7. The syngas was assayed by micro-GC in Tests 1–7, while the FTIR was used in Test 7 only.

The analysis of the experimental results obtained in different tests highlighted the fluctuation of the main chemical species in the syngas (CO, CO_2, H_2, CH_4, C_2H_4). For instance, Fig. 1a shows