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Numerical and experimental investigation of downdraft gasification of woody residues

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HIGHLIGHTS

- ▶ Develop a tool which allows evaluating the effect of the biomass loading rate and moisture content.
- ▶ The model satisfactorily represents the gasifier behavior.
- ▶ As the cold wave overcomes the hot wave no throat stabilization occurs.
- ▶ When the biomass loading rate is increased up to 87.5 kg/h, no throat stabilization occurs.

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ABSTRACT

A pilot scale throated downdraft gasifier was operated with vine prunings as feedstock to assess the effect of biomass loading rate on process performance. A distributed 1D model of mass and heat transfer and reactions was applied to aid the interpretation of experimental evidence. The model takes into account peculiar gasifier design features (air inlets and throat) and it reproduces satisfactorily the temperature profiles and the mass fluxes of gaseous species at different biomass loading rates. The integration of pilot-scale experiments and numerical simulations provides sound indications for the gasifier operation. In particular, simulations performed at different loading rates and feedstock humidity show that steady state operation and stable performance of the gasifier rely on the thermal balance between the enthalpy of cold biomass moving downward and the counter-current radiative heat fluxes moving upward from the oxidation zone. This balance can be destabilized by high loading rate and moisture contents.

1. Introduction

Downdraft gasifiers are the most widespread reactors for small scale electricity production from biomass (Martinez et al., 2012). The assessment of the technological reliability of downdraft gasification relies on pilot scale tests. At this scale, control of operating conditions and evaluation of process parameters are often more problematic than at laboratory scale, and the interpretation of the experimental data may result uncertain because of the spatial and temporal resolution of measurements. Kinetic models may overcome this limitation by taking into account several phenomena involved in the process and providing rather detailed information not directly accessible through experiments (Arnavat et al., 2010).

There are many literature works dealing with the kinetic modeling of fixed bed gasifiers and combustors (Hobbs et al., 1992; Bryden and Ragland, 1996; Di Blasi, 2000; Shin and Choi, 2000; Yang et al., 2003; Tinaut et al., 2008). These models are generally validated on laboratory scale experimental data, and they require to be tuned when they are extended to the description of larger scale systems, particularly because specific design features need to be accounted for to achieve a reliable process and reactor description. For example, full scale downdraft gasifiers (Dogru et al., 2002; Balu and Chung, 2012; Pathak et al., 2008) are often provided with a restricted section called throat which plays an important role in reducing the tar concentration, but available mathematical models does not usually take into account this feature.

Kinetic models of fixed bed gasifiers and combustors typically exhibit the following features:

- → solid and gas motions are treated according to a plug flow description with no momentum transport;
- → particles are assumed thermally thin, spherical and all identical in size;

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Nomenclature

a_s	specific area of the particle, $m^2\ m^{-3}$
C_i	concentration of the gaseous compound i, $kmol\ m^{-3}$
C_g	gas phase density, $kmol\ m^{-3}$
c_{pi}	specific heat, (gas) $J\ kmol^{-1}\ K^{-1}$ (solid) $J\ kg^{-1}\ K^{-1}$
D_{reat}	gasifier diameter, m
d_p	particle size, m
d_{p0}	initial particle size, m
h_i	specific enthalpy, (gas) $J\ kmol^{-1}$ (solid) $J\ kg^{-1}$
h_{gs}	convective gas–solid heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
h_{gw}	convective gas-wall heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
h_{sw}	conductive solid-wall heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
I^+	radiation intensity in the positive direction, $W\ m^{-2}$
I^-	radiation intensity in the negative direction, $W\ m^{-2}$
k_j	kinetic constant, (depends on the reaction rate expression)
k_m	mass transfer coefficient, $m\ s^{-1}$
q_{cgs}	convective gas–solid heat flux, $W\ m^{-3}$
q_{cgw}	convective gas-wall heat flux, $W\ m^{-3}$
q_{kg}	conductive intra gas heat flux, $W\ m^{-3}$
q_{ks}	conductive intra solid heat flux, $W\ m^{-3}$
q_{ksw}	conductive intra solid-wall heat flux, $W\ m^{-3}$
q_{mgs}	gas–solid mass transfer heat flux, $W\ m^{-3}$
q_{rgs}	radiative gas–solid heat flux, $W\ m^{-3}$
q_{rs}	radiative intra solid heat flux, $W\ m^{-3}$
t	time, s
R_j	reaction rate, $kmol\ m^{-3}\ s^{-1}$
T_o	reference temperature, K
T_g	gas phase temperature, K
T_s	solid phase temperature, K
T_w	gasifier wall temperature, K
U_g	gaseous phase velocity, $m\ s^{-1}$
U_s	solid phase velocity, $m\ s^{-1}$
z	axial coordinate, m
α	char reactivity tuning parameter, –
ΔHj	heat of reaction, (gas) $J\ kmol^{-1}$ (solid) $J\ kg^{-1}$
ε	bed void fraction, –
z	axial coordinate, m
λ_g	gas conductivity, $J\ m^{-1}\ K^{-1}$
λ_s	solid conductivity, $J\ m^{-1}\ K^{-1}$
ν_{ij}	stoichiometric coefficient, –
ρ_{bio}	dry biomass bulk density, $kg\ m^{-3}$
ρ_{char0}	char bulk density, $kg\ m^{-3}$
ρ_i	bulk density of the i-component of solid phase, $kg\ m^{-3}$
ρ_{moi}	biomass moisture bulk density, $kg\ m^{-3}$

→ heterogeneous reactions are taken into account with dedicated sub-models;
→ axially and radially uniform gas and solid flow.

Different approaches are available for the description of the gas phase chemistry: equilibrium (Hobbs et al., 1992), finite rate kinetics (Di Blasi, 2000), finite rate kinetics + mixing (Yang et al., 2003). The models usually take into account all the heat fluxes and typically intra-solid radiation is represented according to the Schuster and Schwarzschild equation (Shin and Choi, 2000).

In this work, a mathematical model, based on literature kinetic, mass transfer and heat transfer sub-models, is adapted to represent the behavior of a pilot scale throated downdraft gasifier during a series of experimental tests with vine prunings. The aim is to develop a tool which allows evaluating the effect of the biomass loading rate and moisture content on process performance. After validation, the model is used to evaluate the effect of operating parameters which are of interest for the improvement of the gasifier performance and to assess its operational limits.

2. Methods

2.1. Experimental setup

The gasification facility is located at CRIBE (Interuniversity research centre on biomass for energy) and it is extensively described in Simone et al. (2012). The downdraft gasifier can operate with woodchips produced from forest maintenance and other residues or energy crops with similar physical and morphological properties, but cannot handle residues such as olive pomace or sawdust. In this work vine prunings (Moisture 17.6%, VM 66.6%, FC 13.7%, Ash 2.1%, Lower calorific value 14.8 MJ kg^{-1}, dry bulk density 235 kg m^{-3}) were used as feedstock for the experimental tests. Fig. 1a shows the section of downdraft gasifier. The biomass is fed to the top of the gasifier via a screw conveyor. The plant is operated slightly below atmospheric conditions due to a blower positioned at the end of the gas clean-up line; consequently air enters the gasifier through four nozzles positioned in the throated section of the gasifier. The biomass is supported on a grate at the bottom of the gasifier. As the gasification reactions occur, the biomass becomes smaller in size and the solid residue falls under the grate. The produced gas moves upward from the bottom of the gasifier in an external ring and enters the clean-up system. The gasifier is ignited with a flare which is positioned for fifteen seconds at the top of each nozzle. The syngas productivity can be regulated modulating a valve positioned on a by-pass of the blower. Closing the by-pass valve increases the air adduction to the plant and thus the syngas flow-rate and the biomass consumption. In response to the higher biomass consumption the gasifier is charged more frequently by the feeding system to keep constant the biomass level in the gasifier. A portable K-thermocouple was used to evaluate the temperature profile in the gasifier throat into the gasifier through the gasifier nozzles. The syngas flow-rate was measured with a flow-meter positioned after the blower. The gas composition was analyzed by a micro-GC Agilent 3000.

2.2. Mathematical modeling

2.2.1. Modeling approach

The gasifier is represented with a 1D domain. The model takes into account the lower portion of the gasifier only, since during the experimental tests it was recognized that in the upper section the low temperature does not allow for significant reactions. The modeling approach, schematized in Fig. 1b, is similar to that followed by other authors (Shin and Choi, 2000; Di Blasi, 2000; Tinaut et al., 2008) and it is based on the separate treatment of the gas and the solid phase. The two phases are coupled via mass and energy fluxes. The mixing of the phases is described with a sequence of plug flow-reactors. The first couple of PRFs describe the portion of the gasifier before the air inlet. No gas enters from the top of the gasifier, thus the PFR of the gas phase in this part of the reactor takes into account the gas generation due to drying and devolatilization of the biomass. The first gas phase PFR is connected to a completely stirred tank reactor (CSTR), which takes into account the air (or other gasifying agent) inlet through the four nozzles. The resulting stream from the CSTR provides the inputs for the sec-