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Development of a new steady state zero-dimensional simulation model for woody biomass gasification in a full scale plant

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ABSTRACT

A new steady state zero-dimensional simulation model for a full-scale woody biomass gasification plant with fixed-bed downdraft gasifier has been developed using Aspen Plus®. The model includes the technical characteristics of all the components (gasifier, cyclone, exchangers, piping, etc.) of the plant and works in accordance with its actual main control logics. Simulation results accord with those obtained during an extensive experimental activity. After the model validation, the influence of operating parameters such as the equivalent ratio, the biomass moisture content and the gasifying air temperature on syngas composition have been analyzed in order to assess the operative behavior and the energy performance of the experimental plant. By recovering the sensible heat of the syngas at the outlet of the gasifier, it is possible to obtain higher values of the gasifying air temperature and an improvement of the overall gasification performances.

1. Introduction

Recently the growing awareness of the shortage of the traditional energy sources and the concern for environmental protection have encouraged the wider use of renewable energy sources. Among these, biomass is certainly one of the most important because of its inexhaustibility and wide availability. In addition, more than wind and photovoltaic, energy conversion of biomass can create concrete local economic opportunities.

The exploitation of energy through biomass comes off bio-chemical and thermo-chemical processes [1]. Bio-chemical process involves biomethanization of biomass, characterized by low cost effectiveness and efficiency. Actually, the three main thermo-chemical processes are combustion, pyrolysis and gasification. Combustion, apart from the applications in small fireplaces and stoves, is used mainly to supply heat and power by means of large scale systems (typically above 500 kW_e), and the net efficiency for electricity generation is usually very low and ranges from 15% to 20% for the smallest plants (<1 MW_e) [2]. Pyrolysis converts biomass to bio-fuels and bio-char in absence of oxygen (O_2), but the application of this technology is limited due to the thermal system complexity and the low quality of the fuels that are produced. Gasification [3] converts biomass through a partial oxidation into a gaseous mixture, called *syngas*, and represents, especially in the low power range (<500 kW_e), the process with the greatest development prospects mainly for its high electric efficiency (20–25%) [4,5]. Other advantages of gasification are the plant simplicity and the lower capital cost for small scale applications with respect to other technologies. The main drawback is represented by the syngas cleaning system complexity and efficiency.

The development of numerical simulation models is an important tool in order to provide more accurate qualitative and quantitative information on biomass gasification. The possible approaches for the modeling of the gasification process are: steady state models, transient state models and models based on the computational fluid dynamics. The steady state models, that do not consider the time derivatives, are further classified as kinetic rate models and kinetics free equilibrium models [6–9]. For the evaluation of the syngas composition and temperature as function of the process parameters, the kinetics free equilibrium models are the most preferred models because they are very simple and reliable. They have the inherent advantage of being generic but, at the same time, they have thermodynamic limitations, even though researchers have successfully demonstrated that this approach describes sufficiently well the gasification process in downdraft gasifiers [10–13].

A commercial code, such as Aspen Plus®, can be usefully and effectively adopted for the construction of a reliable kinetic free

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Nomenclature

CGE	cold gas efficiency (–)
Cp_a	specific heat of the wind air outside of the gasifier (J/kg K)
Cp_i	specific heat of the air/syngas within chipped biomass bed (J/kg K)
$D_{e\_insulation}$	external diameter of the ceramic fiber insulation (m)
$D_{e\_refractory}$	external diameter of the protective refractory layer (m)
D_{e_shell}	external diameter of the reactor shell (m)
D_i	internal diameter of the protective refractory layer (m)
d_p	mean equivalent diameter of the chipped biomass that is supposed as sphere (m)
E_m	the emissivity of the cover surface of the external thermal insulation of the gasifier (–)
ER	equivalent ratio (–)
k_a	conductivity of the wind air outside the gasifier (W/m K)
k_i	conductivity of the air/syngas within chipped biomass bed (W/m K)
$k_{insulation}$	conductivity of the ceramic fiber insulation (W/m K)
$k_{refractory}$	conductivity of the refractory layer (W/m K)
k_{shell}	conductivity of the shell (W/m K)
L	length of the reactor (m)
l	height of the chipped biomass bed within the gasifier (m)
LHV	lower heating value (kJ/kg)
LHV_b	lower heating value of biomass (kJ/kg)
LHV_s	lower heating value of the syngas (kJ/kg)
MC	moisture content (–)
$\dot{m}_b$	biomass mass flow (kg/s)
$\dot{m}_s$	syngas mass flow (kg/s)
m_{a_a}	actual gasifying air mass flow (kg/s)
m_{a_s}	stoichiometric gasifying air mass flow (kg/s)
Nu_a	Nusselt number for the convective heat exchange between the wind air and the cover surface of the external thermal insulation of the gasifier (–)
Nu_i	Nusselt number for the convective heat exchange between the air/syngas and the internal surface of the refractory layer of the gasifier (–)
Pr_a	Prandtl number of the wind air outside of the gasifier (–)
Pr_i	Prandtl number of the air/syngas within chipped biomass bed (–)
$\dot{Q}$	thermal power that is dispersed by the gasifier into the environment (W)
R_{c1}	conductive thermal resistance of the internal refractory layer (K/W)
R_{c2}	conductive thermal resistance of the gasifier shell (K/W)
R_{c3}	conductive thermal resistance of the external thermal insulation of the gasifier shell (K/W)
R_e	thermal resistance of the convective heat exchange between the wind air and the cover surface of the external thermal insulation of the gasifier shell (K/W)
Re_a	Reynolds number of the wind air outside of the gasifier (–)
Re_i	Reynolds number of the air/syngas within chipped biomass bed (–)
R_i	thermal resistance of the convective heat exchange between the air/syngas and the internal surface of the refractory layer of the gasifier (K/W)
R_r	equivalent thermal resistance of the radiative heat exchange between the cover surface of the external thermal insulation of the gasifier shell and the environment (K/W)
R_{tot}	total thermal resistance from the reactor core to the environment (K/W)
T_e	environment temperature (K)
T_p	the temperature of the cover surface of the external thermal insulation of the gasifier (K)
T_r	mean temperature of air/syngas within the reactor (m/s)
u_a	velocity of the wind air outside of the gasifier (m/s)
u_i	mean velocity of the air/syngas across the chipped biomass bed within the gasifier (m/s)

Greek symbols

ΔP	pressure drop of the air/syngas across the gasifier (Pa)
ε	mean porosity of the chipped biomass bed within the gasifier (–)
μ_a	dynamic viscosity of the wind air outside of the gasifier (kg/m s)
μ_i	dynamic viscosity of the air/syngas across the chipped biomass bed within the gasifier (kg/m s)
ρ_a	density of the wind air outside of the gasifier (kg/m^3)
ρ_i	density of the air/syngas across the chipped biomass bed within the gasifier (kg/m^3)
σ	the Boltzmann constant (W/m^2 K^4)

equilibrium simulation model. This article aims at presenting an innovative simulation approach, where the whole experimental gasification plant, containing all the elements such as cyclone, heat exchangers and turbomachineries, works following the main control logics of the real plant. Besides, it gives an experimental contribution to the validation of a zero-dimensional steady state simulation model of a full-scale wood-fueled downdraft gasifier. Furthermore, it tries to demonstrate that it is possible to define and tune a reliable equilibrium Aspen Plus® simulation model using detailed experimental data of a real gasification plant (equipment and streams). This model makes it possible to effectively predict the performance of the plant over a wide range of operative conditions.

To the best of the authors' knowledge, simulative models for a whole gasification plant with fixed-bed downdraft gasifier have never presented in literature considering the actual performance characteristics and operative behavior of the plant equipments.

Hence, the work described in this paper is very innovative and can be an useful tool for the developers and users of biomass gasification combined heat and power plants.

On the other hand, there are several papers that describe a steady-state biomass gasification model using Aspen Plus®, mainly in the field of fluidised bed gasifiers. These are briefly summarized below. Ramzan et al. [14] reported an interesting comparative analysis between the simulation performances of a lab-scale updraft biomass gasifier and the experimental data obtained in literature. Fu et al. [15] analyze without an experimental validation how the performances of an autothermal biomass gasifier are affected by the gasifying air flow and temperature. Doherty et al. [16–18] using experimental data from literature proposed and validated an Aspen Plus® model based on the Gibbs free energy minimization for a circulating fluidised bed gasifier and for a steam blown dual fluidised bed gasifier, in order to show the dependence of the gasifier performance on the gasifying air temperature.