MODELING AND DYNAMIC SIMULATION OF STRATIFIED DOWNDRAFT GASIFIERS

Gh. LAZAROIU[a], U. DESIDERI[b], C. STROE[a], , I. BOGDAN[a]

(a) Faculty of Power Engineering,Politehnica University of Bucharest
e-mail: glazaroiu@yahoo.com
(b) University of Study Perugia

Abstract: *In this paper, a one-dimensional model for biomass gasification in a stratified concurrent (downdraft) reactor is presented. Heat and mass transfer across the bed are coupled with moisture evaporation, biomass pyrolysis, char combustion and gasification, gas-phase combustion and thermal cracking of tars. Numerical simulation resulted in predicting the influence of model parameters, kinetic constants and operational variables on process dynamics, structure of the reaction front and quality of the producer gas. For high values of the air-to-fuel ratio and of the primary pyrolysis rate, the process is top-stabilized, resulting in a high conversion efficiency and good gas quality. As the air flow is decreased below a critical limit value, the reaction front becomes grate-stabilized. The two different configurations are largely determined by the gas-phase combustion of volatile pyrolysis products.*

Keywords: biomass, gasification, dynamic behaviour, numerical simulation.

1. INTRODUCTION

Biomass and waste are widely recognized to be a major potential for energy production. Gasification enables conversion of this material into combustible gas, mechanical and electrical power and synthetic fuels and chemicals. In principle, the gasification units employed for coal can also be applied for biomass and waste, but significant differences exist between the two fuel categories. Updraft, countercurrent gasifiers are well suited for the conversion of low-reactive char into gas. When biomass is pyrolyzed, gases and tars represent 70-90% of the total mass fed, whereas only 30-10 % is a highly reactive char. In updraft air gasification, the oxygen is consumed at the grate, essentially through partial combustion of char. The resulting hot gases cause char gasification and biomass pyrolysis.

2. KINETIC MODEL

The relatively low temperatures and the absence of oxygen result in large amounts of tars in the producer gas [2]. Kinetics-free, equilibrium models can predict the exit gas composition, given the solid composition and the equilibrium temperature, but they cannot be used for reactor design. However, the description of the “flaming pyrolysis” that is biomass pyrolysis and combustion of volatile pyrolysis products, is still based on equilibrium models or on highly simplified treatments, which assume the existence of a stable combustion zone with infinitely oxygen conversion rate near the air inlet. Furthermore, these models describe steady-state conditions. Thus, they do not allow the prediction of the dynamic behavior of stratified gasifiers and of the different modes of stabilization of the reaction front and thus the size of the reduction zone. This study proposes a more advanced, dynamic model, which includes finite rate kinetics for biomass pyrolysis and combustion of char, gaseous species and tars. The model was used to simulate the effects of changes in transport coefficients, chemical kinetics and operating conditions on the performances of the gasification process, in view of reactor design and optimization, especially in relation to the dynamic behavior of downdraft reactors, i.e. to top- or grate-stabilized operation.

The stratified gasified model is based on mass and energy balances for the solid phase and mass and energy balances for the gas phase, written for a one-dimensional, unsteady state system. Species considered are: oxygen, nitrogen, hydrogen, steam, carbon dioxide, carbon monoxide, methane and hydrocarbons (which also include tars). The pressure drop in the reactor is modeled using the generalized Darcy law but, given the large bed permeability, simulations have been carried out with the assumption of constant pressure (the gas velocity is determined from the continuity equation and the density of the mixture from the ideal gas law). As the concurrent flows of solid and gas descend across the reactor, several processes take place, namely, moisture evaporation, biomass pyrolysis, char combustion and gasification, combustion of the gases and thermal cracking of the tars, in accordance with the schematic representation reported in *figure 1.*

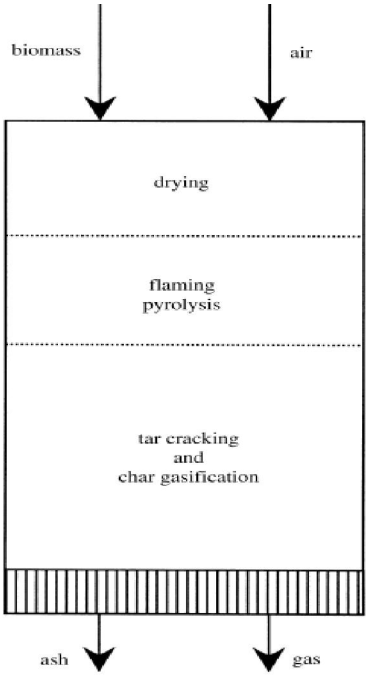


Figure 1. Schematic of the stratified concurrent (downdraft) gasifier

The chemical reactions are:

- Pyrolysis reactions

$$B \xrightarrow{k_{p1}} v_C CHAR + v_G GAS + v_T TAR$$

$$TAR \xrightarrow{k_{p2}} GAS_2$$

- Gas-phase combustion

$$(tar)\, CH_{1.522}O_{0.0228} + 0.867 O_2 \xrightarrow{k_{c1}} CO + 0.761 H_2O$$

$$CH_4 + 1.5 O_2 \xrightarrow{k_{c2}} CO + 2H_2O$$

$$2CO + O_2 \xrightarrow{k_{c3}} 2CO_2$$

$$H_2 + O_2 \xrightarrow{k_{c4}} 2H_2O$$

- Gas-phase water gas shift

$$CO + H_2O \xleftrightarrow{k_{wg}} CO_2 + H_2$$

- Heterogeneous reactions of char

$$CH_\alpha O_\beta+\gamma O_2\xrightarrow{k_{c5}}\left(2-2\gamma-\beta+\frac{\alpha}{2}\right)CO+\left(2\gamma+\beta-\frac{\alpha}{2}-1\right)CO_2+2\alpha H_2$$

$$CH_\alpha O_\beta+CO_2\xrightarrow{k_{g1}}2CO+\beta H_2O+\left(\frac{\alpha}{2}-\beta\right)H_2$$

$$CH_\alpha O_\beta+\left(2-\frac{\alpha}{2}+\beta\right)H_2\xrightarrow{k_{g2}}CH_4+\beta H_2O$$

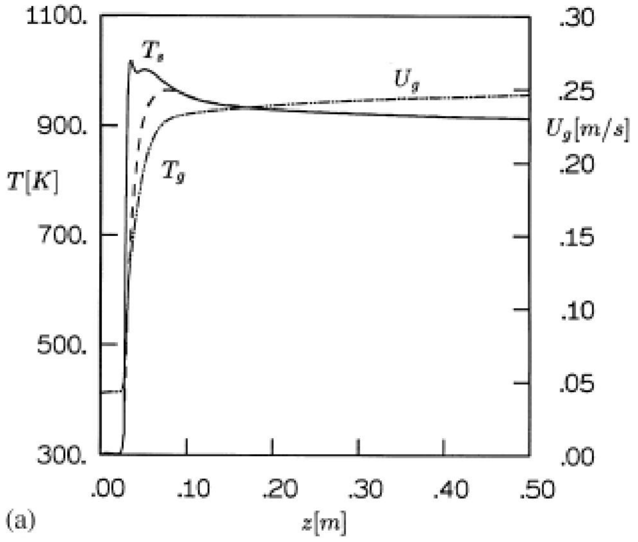
$$CH_\alpha O_\beta+\left(1-\beta\right)H_2O\xrightarrow{k_{g3}}CO+\left(1-\beta+\frac{\alpha}{2}\right)H_2$$

Where: *B* biomass (wood);
c_1 tar combustion;
c_2 methane combustion;
c_3 carbon monoxide combustion;
c_4 hydrogen combustion;
c_5 char combustion;
gw gas/wall;
g_1 carbon dioxide gasification;
g_2 hydrogen gasification;
g_3 steam gasification;
wg water gas shift;
k_m mass transfer coefficient, m/s.

A one-step global reaction is considered, where the fractions of gases, tars and chars produced and the gas composition should be specified [3]. Tars undergo secondary cracking in the void spaces of the bed (one-step global reaction), to produce secondary gases, whose composition should again be specified. The size (volume) and the solid velocity of the spherical particles remain constant as the bed density decreases during moisture evaporation and biomass devolatilization. Consequently, the porosity of this portion of the bed varies. Combustion and gasification reactions of char are heterogeneous and are described by the unreacted core, shrinking particle model, where a steep reaction zone propagates through the isothermal char.

3. RESULTS

Two mechanisms responsible for the global reaction rate are considered: diffusion through the gas film, surrounding the particle, and intrinsic chemical kinetics. To account for the simultaneous effects of the two resistances, an effective volumetric reaction rate is introduced, based on the assumption of a linear dependence of the reaction rate on the oxidizing/gasifying species concentration. As a consequence of the heterogeneous reactions, the particle diameter shrinks and the density of the bed (and porosity) remains constant, causing a gradual decrease in the solid velocity. The minimum size of the particle and consequently the maximum particle density number depend on the ash content of the solid. Simulations have been carried out for biomass particles 1 cm thick, with an ash content of 10.5 and an initial moisture content of 10 d.b. (dry basis). A steady-state scenario (time equal zero is referred to this initial condition), corresponding to a reaction zone located near the top of the reactor, has been chosen as initial condition for the simulations by varying model parameters, kinetic constants (pyrolysis, gasification, combustion) and the two operational variables: the biomass feed rate and the air-to-biomass ratio. A first set of simulations has been carried out by varying the biomass feed rate in the range 7-18 kg/h for an air-to-fuel ratio of 1.5. The effects of the air-to-fuel ratio have also been investigated for variations in the range 0.6-2.6 for a biomass feed rate of 18 kg/h. In this section, the effect of these parameters on the process characteristics are discussed. The main characteristics of the gasification process can be observed



from *figures 2* and *3*.

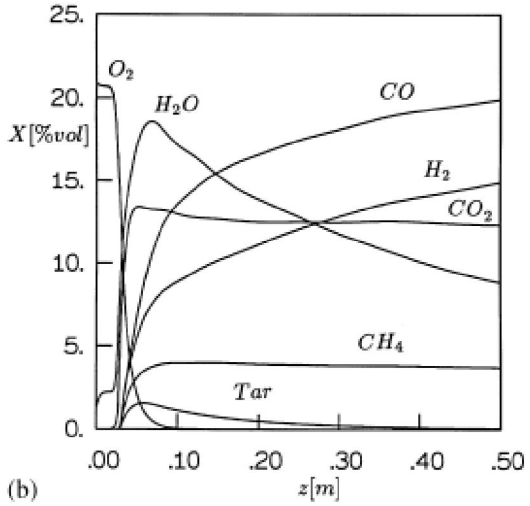


***Figure 2*. A. Axial profiles of solid and gas temperature and gas velocity**
B. Axial profiles of species molar fractions

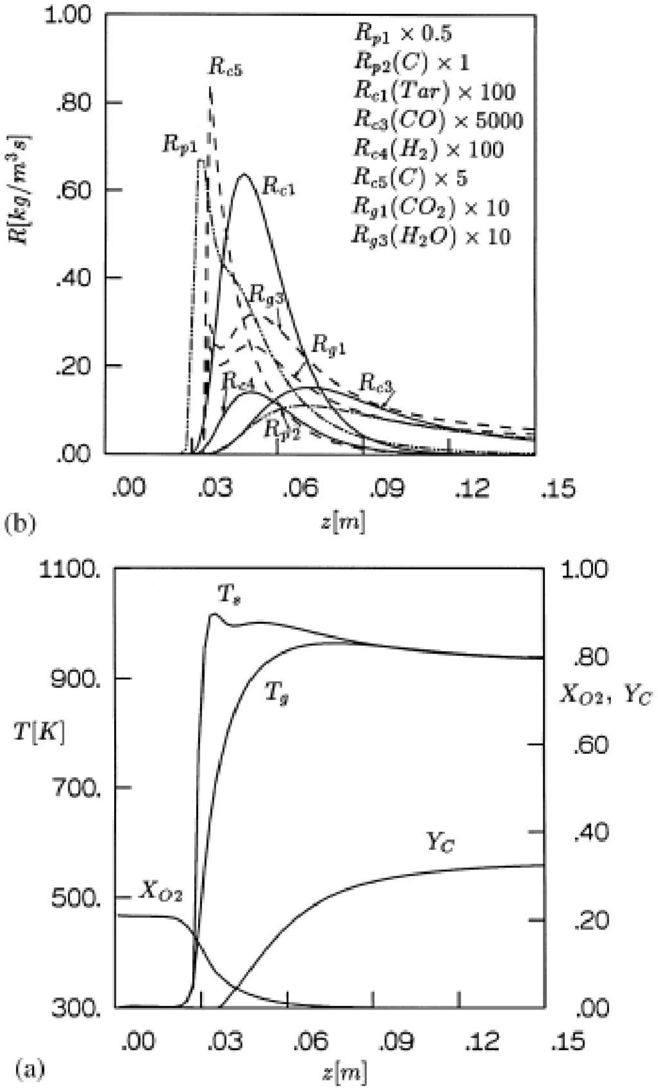


***Figure 3*. A. Structure of the reaction front: oxygen molar fraction, char mass fraction and temperature profiles**
B. Structure of the reaction front: axial profiles of reaction rates

It should be noted that the moisture evaporation front is very steep, probably as a consequence of the highly simplified description (diffusional resistance only), which does not include intra-particle temperature and moisture gradients. The endothermicity of the process has been found to contribute significantly to limit the maximum temperature. Biomass devolatilization is also characterized by spatial temperature and solid-phase species gradients much larger than those observed for the updraft configuration. Indeed, the concurrent solid and gas flow towards the combustion zone makes the heat transfer difficult towards the virgin solid region. Differences between the solid and gas temperatures are significant at the leading edge of the reaction zone, but they tend to disappear in the reduction zone. Among the gasification products, the most abundant is CO, followed by H_2 and CH_4. The tar content of the gas is very small, while H_2O and CO_2 are still present in significant amounts. On the whole, the processes of primary and secondary pyrolysis and the homogeneous and heterogeneous combustion reactions take place simultaneously, with high rates mainly along a distance of about 0.2 m.

***Table 1.* Comparison between the predicted and measured composition of the producer gas**

Species	Groeneveld (1980)	Chern and Fan (1985)	Wang&Kinoshita	This study
CO	17	18-20	18-20	20.3-18.5
H2	14	12-16	10-14	16.8-9.8
CO2	13.6	14.16	9.6-11	15.3-9.4
CH4	0.9	2.5	2.5-4.8	4.5-2.4
N2	46.5	53-45	52-54	43-60

Indeed, in agreement with previous findings, it has been found that the gas composition is mainly determined by the composition of the pyrolysis gas and the equilibrium conditions of the water gas shift reaction, as it is shown in *table 1.*

4. CONCLUSION

A mathematical model has been formulated, which includes the description of all the main chemical and physical processes taking place during the fixed-bed downdraft gasification of lignocelluloses fuels. The model predictions reproduce well, from the qualitative point of view, the dynamic behavior and the steady-state configurations, on dependence on the air/fuel feed rate, of downdraft wood gasifiers. Gas-phase combustion and primary pyrolysis appear to play a controlling role for the mode of stabilization of the reaction It should be noted that a correct prediction of the tar content of the gaseous effluents is important for an effective design of the gasifier, the selection of the optimal operation condition and the choice of the most adequate gas cleaning procedure. Another important factor for the conversion process is the char reactivity (gasification and combustion), which in the model is described by the unreacted core model, on the basis of the effective mass transfer coefficient and the intrinsic kinetics. Critical points in this approach, which needs further investigation, are represented by the infinitely thin reaction zone and by the absence of the char concentration in the rates of the gasification reactions. Finally, more reliable input data are needed for the simulation of the gasification process, in relation to both transport coefficients and intrinsic reaction kinetics. Indeed, these have been, for large part, investigated under thermo gravimetric conditions, which do not reproduce the true gasification conditions.

Bibliography:

[1] Bhattacharya, A., Salam, L., Dudukovic, M. P., & Joseph, B. (1986). Experimental and modelling studies in fixed-bed char gasification. *Industrial & Engineering Chemical Process Design and Development*, *25*, 988.
[2] Reed, T. B., & Markson, M. (1985). Biomass gasification reaction velocities. In R. P. Overend, T. A. Milne, L. K. Mudge, *Fundamentals of Thermochemical Biomass Conversion* (p. 951). Amsterdam: Elsevier.
[3] Di Blasi, C. (1993). Modeling and simulation of combustion processes of charring and non-charring solid fuels. *Progress in Energy and Combustion Science*, *19*, 71.
[4] Wang, Y., & Kinoshita, C. M. (1994). Temperature fields in downdraft biomass gasification, *Proceedings of the International Conference on Advances in Thermochemical Biomass conversion* (p. 280).
[5] Walawender, W. P., Chern, S. M., & Fan, L. T. (1985). Wood chip gasification in a commercial downdraft gasifier. In R. P. Overend, T. A. Milne & L. K. Mudge, *Fundamentals of Thermochemical Biomass Conversion* (p. 911). Amsterdam: Elsevier.
[6] Groeneveld, M. J., & van Swaaij, W. P. M. (1980). Gasification of char particles with CO_2 and H_2O. *Chemical Engineering Science*, *35*, 307.