KINETIC AND TRANSFER MODELING OF CHAR GASIFICATION IN DOWNDRAFT BIOMASS GASIFIER

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ABSTRACT:

A 2-D numerical model for the reduction zone of a biomass downdraft gasifier is developed. It is based on the mass and energy balances for the solid and fluid phases coupled with the chemical kinetics. The obtained model results are compared with published experimental data and good agreement between the values is showed. The temperature and species concentration profiles inside the gasification zone can be studied for various parameters such as the inlet conditions (temperature and concentration) and geometry such as bed length and diameter.

Key words: biomass, gasification, 2-D modeling, downdraft gasifier

NOMENCLATURE:

A_i	Frequency factor	s^{-1}	greek		
C_j	concentration Species j	mol/m^3	ρ	Gas density	$Kg.m^{-3}$
C_p	molar heat capacity	$J.K^{-1}$	λ	Gas thermal conductivity	$W.m^{-1}.K^{-1}$
CRF	Char reactivity factor	-	ε	Bed Porosity	-
C_t	Total gas concentration	mol/m^3	μ	Dynamic viscosity	Pa.s
D_j	Diffusion coefficient	$m^2.s^{-1}$	ΔH	Reaction enthalpy	$J.mol^{-1}$
E_i	Activation energy	s^{-1}			
K	Bed Permeability	m^2	subscript		
P	Pressure	Pa	g	Gas phase	
R	Universal gas constant	$J.mol^{-1}.K^{-1}$	s	Solid phase	
R_i	Reaction rate	s^{-1}	i	reaction	
S_c	Continuity Source term	$Kg/m^3.s$	j	specie	
T	Temperature	K	t	total	
U	Radial velocity	$m.s^{-1}$			
W	Axial velocity	$m.s^{-1}$			
z	Axial distance	mm			

1. INTRODUCTION

Biomass has used for centuries as a source of heat for humans. Actually, thanks to new technologies, it can be used to provide several kinds of renewable energies. Among these technologies, gasification is an interesting way to upgrade the biomass energy content. It consists of the conversion of organic materials into a fuel gas.

Biomass gasification can be achieved in many reactor types depending upon several criterions such as fuel properties and the desired application. The downdraft gasifier is known to yield a gas with low tar content, and it represents a good tool for the conversion of biomass into syngas.

In recent years, char gasification in downdraft gasifier was studied by several authors [1-9] through the development of mathematical models. These models represented two main approaches: the equilibrium modeling [2,3, 7] and the kinetic modeling [1,4-7].

Halouani and Golli [2] performed an experimental study on a downdraft gasifier coupled with a cooling and cleaning system and they developed a numerical model using equations of the main reactions of gasification as well as the mass and energy balances. Zainal et al. [3] studied an equilibrium gasification model based on the equilibrium constants. Giltrap et al. [4] developed a 1-D model of the reduction zone of a downdraft biomass gasifier to predict the composition of the producer gas under steady state operation. Babu et al. [5] modified the model of Giltrap by incorporating a variation of the char reactivity factor along the reduction zone. Jayah et al. [8] presented an experimental and theoretical 1-D model for gasification in downdraft gasifier. The developed model assumes that a single char particle moves downward along the vertical axis of the gasifier.

In the present study, we propose a 2-D model of char gasification in downdraft gasifier to account for the radial variation of the temperature, gases fractions and properties along the gasification zone.

2. SYSTEM DESCRIPTION

The downdraft gasifier (Figure 1) is a variety of the fixed bed type. It is characterized by the co-current movement of biomass and gas. The air is introduced at the top or through the sides, and a grate is placed at the bottom to support the fuel and the ash.

In the downdraft gasifier, biomass decomposition occurs progressively as temperature increases. The organic material fed at the top of the gasifier undergoes 4 steps namely drying, pyrolysis, oxidation and reduction to generate a combustible gas mixture.

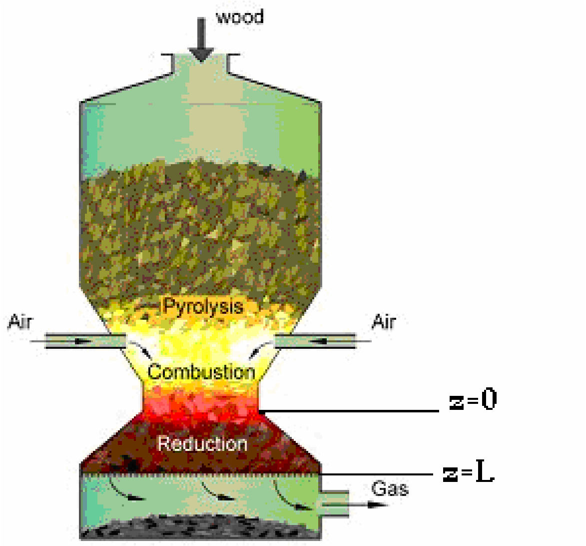

Figure 1. Downdraft biomass gasifier [10].

2.1 Drying

When biomass is introduced, it undergoes drying as a first step. In fact, a part of the heat generated in the oxidation region causes the water evaporation and thus the moisture content is removed. The downdraft gasifier shows little flexibility with respect to biomass moisture [9] and a great moisture level would affect the efficiency of the conversion.

2.2 Prolysis-oxidation

Pyrolysis is the second step encountered in the gasifier. In this region, the volatile matter is released and is immediately combusted, living behind the solid char. The combustion provides further heat for the process continuation. This description shows that pyrolysis and combustion are overlapping in the downdraft gasifier and therefore are described simultaneously in the literature by a single process called pyro-oxidation process [7] or flaming-pyrolysis [8,9].

2.3 Gasification

In this region, called also the reduction zone, the combustion products, mainly H_2O and CO_2, react with the reaming char to yield combustible gases mainly CO and H_2. This step is the slowest step in the overall process, and is so considered as the rate determining step [9].

3. MATHEMATICAL FORMULATION

3.1 Assumptions

The elaborated model is based on the following assumptions:

- The model is 2-D (axi-symmetric)
- The gasifier is assumed to load in a steady state.
- All the sub processes (carbonization, tar cracking and combustion) have been achieved before the reduction zone. Thus, neither tar nor oxygen is present in this zone.
- The char consists of pure carbon and is subsequently renewed.
- The gas flowing in the reduction zone consists of six species: N_2, CO, H_2, CO_2, H_2O, and CH_4.
- Ideal gas law is applicable to all gas species present.
- Heat losses are neglected through outside walls.
- The local thermal equilibrium is assumed between the solid and gas phases.

3.2 Kinetic scheme

Based on the literature [1,4-7], four reactions are considered in the reduction zone to predict the concentrations of six gaseous species (N_2, CO, H_2, CO_2, H_2O, and CH_4):

Steam gasification reaction: $$\mathrm{C + H_2O \Leftrightarrow CO + H_2} \tag{1}$$

Boudouard reaction: $$\mathrm{C + CO_2 \Leftrightarrow 2CO} \tag{2}$$

Methanation reaction: $$\mathrm{C + 2H_2 \Leftrightarrow CH_4} \tag{3}$$

Steam reforming reaction: $$\mathrm{CH_4 + H_2O \Leftrightarrow CO + 3H_2} \tag{4}$$

The corresponding reaction rate is given by the following expression [7]:

$$R_i = C_t \times CRF \times A_i \exp\left(\frac{-E_i}{RT}\right) \times \left(y_{product} - \frac{y_{reactant}}{K_{eq}}\right) \tag{5}$$

Where C_t is the sum of all species concentrations and CRF represents the char reactivity factor which the expression is taken variable along the reduction zone as [7]: $CRF(z) = 4.0012 \times 10^{-2} \times z - 3.0012$

3.3 Model equations

Based on the model assumptions, the set of conservation equations is given by:

- Continuity equation (gas phase):

$$\frac{1}{r}\frac{\partial(\varepsilon\rho r U)}{\partial r} + \frac{\partial(\varepsilon\rho W)}{\partial z} = S_c \tag{6}$$

- Species conservation (j=H_2O, H_2, CO_2, CO, CH_4 and N_2):

$$\varepsilon\rho U\frac{\partial C_j}{\partial r}+\varepsilon\rho W\frac{\partial C_j}{\partial z}=\frac{1}{r}\frac{\partial}{\partial r}(\varepsilon D_j r\frac{\partial C_j}{\partial r})+\frac{\partial}{\partial z}(\varepsilon D_j\frac{\partial C_j}{\partial z})+R_j \tag{7}$$

- Momentum equation (radial and axial direction respectively):

$$\varepsilon\rho U\frac{\partial U}{\partial r}+\varepsilon\rho W\frac{\partial U}{\partial z}=-\frac{\partial P}{\partial r}-\varepsilon\frac{\mu}{K}U+\mu\left(\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(rU)}{\partial r}\right)+\frac{\partial^2(U)}{\partial z^2}\right) \tag{8}$$

$$\varepsilon\rho U\frac{\partial W}{\partial r}+\varepsilon\rho W\frac{\partial W}{\partial z}=-\frac{\partial P}{\partial z}-\varepsilon\frac{\mu}{K}W+\mu\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial(W)}{\partial r}\right)+\frac{\partial^2(W)}{\partial z^2}\right) \tag{9}$$

- Energy conservation assuming thermal equilibrium between the solid and the fluid phases:

$$\varepsilon\rho UC_p\frac{\partial T}{\partial r}+\varepsilon\rho WC_p\frac{\partial T}{\partial z}=\frac{1}{r}\frac{\partial}{\partial r}(\lambda_e\frac{\partial T}{\partial r})+\frac{\partial}{\partial z}(\lambda_e\frac{\partial T}{\partial z})+\sum\Delta H_iR_i \tag{10}$$

Where λ_e the effective thermal conductivity given by $\lambda_e=(1-\varepsilon)\lambda_s+\varepsilon\lambda_g$

3.4 Boundary conditions

At the top of the reduction zone, the inlet temperature and gas velocity are taken from [4] as T=1200K and W= 1 m.s^{-1}; while the gaseous fractions are those used by Babu et al. [5] which were calculated assuming tar cracking into an equivalent amount of CO, H_2O and CH_4.
At the exit of the reactor, the fully developed condition is used for all variables.

3.5 Solution method

The mass, momentum and energy conservation equations constitute a coupled nonlinear partial differential equations system which are solved using the finite volume method with a staggered non uniform grid.

4. RESULTS

4.1 Model validation

The gas fractions obtained at the exit of the gasifier (i.e. reduction zone) are validated against the experimental data of Jayah et al. [8]. Figure 2 shows the composition of the dry product gas predicted by the model along with the one found experimentally under conditions of 12 % for the moisture content and 2.36 for the air to fuel ratio. The model produced a reasonable agreement with the experimental results with an absolute average deviation of about 11.9 %. The difference is probably due to the complexity of the chemical reactions occurring in the real gasifier, the equilibrium constant, heat loss, and inlet conditions can also affect the results.

4.2 Simulation results

4.2.1 Temperature profile along the gasification zone

Figure 3 shows the simulated temperature profile predicted by the model. The temperature decreases continuously along the length of the reduction zone with the highest variation occurring in the first 100 mm, and lower variation for the remaining part. This fact shows that the extent of the endothermic gasification reactions is high at the beginning, but it decreases rapidly through the reduction zone because of the heat absorption and the consequent temperature drop.

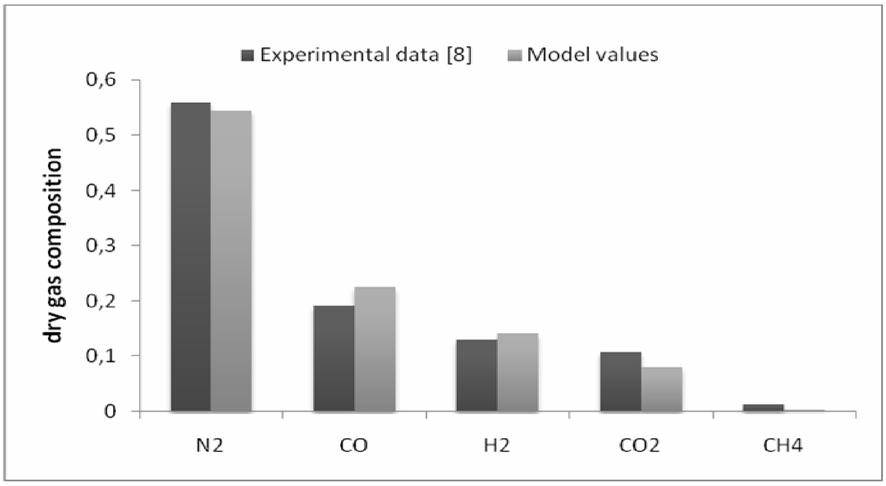

Figure 2. Predicted gas composition compared with experimental measurements

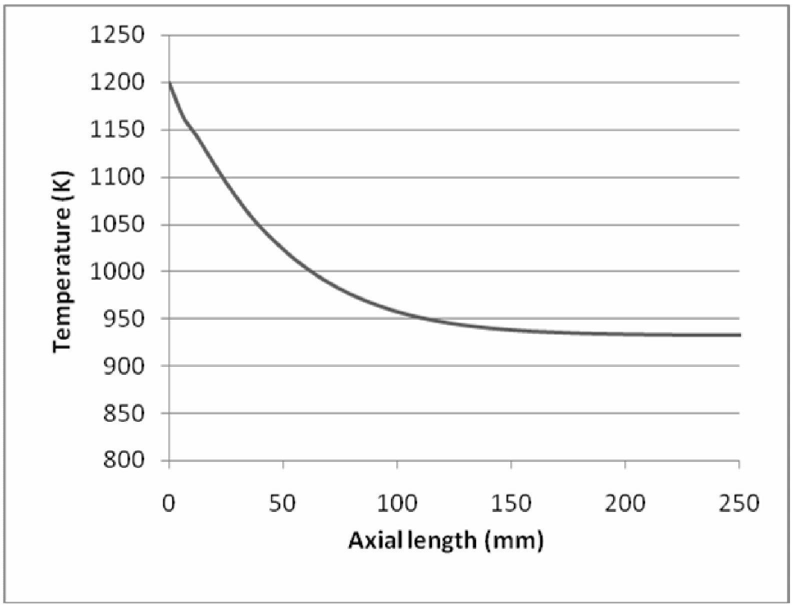

Figure 3. Temperature field inside the gasification zone at r=0

4.2.2 Composition profile along the gasification zone

Figure 4 shows the evolution of each gas species along the reduction zone. As for the temperature field, the same trend is shown here with a high production of hydrogen and carbon monoxide at the initial length, and low variation of the gases fractions at the rest of the bed. Indeed, the rate of production or consumption of a species is related to the heterogeneous reactions which proceed rapidly at the beginning of the bed as concluded above.

5. CONCLUSION

A two-dimensional model for heat and mass transfer is developed for a downdraft gasifier. The results show that the composition of the gases factions at the exit of the gasification zone predicted by the elaborated model is in good agreement with the experimental results. More accuracy would be reached by considering the convective heat transfer between the char and the gas and by modeling the gasification sub-processes (pyrolysis and combustion) to get the input parameters (gas fractions, temperature…) precisely. Giving these initial conditions, the model can be used to study the effect of several operating parameters such as moisture content, air fuel ratio and gasification temperature.

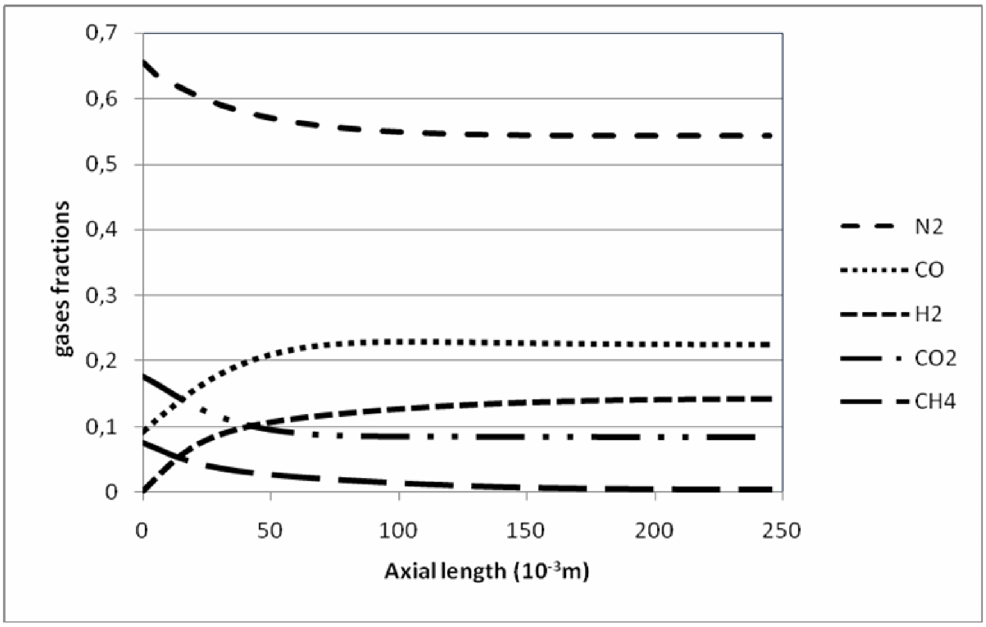

Figure.4 Gases fractions evolution inside the gasification zone at r=0

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