

AIGE CONFERENCE: A KINETIC MODEL FOR A STRATIFIED DOWNDRAFT GASIFIER

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ABSTRACT

A model for a stratified downdraft gasifier has been developed. It has been adapted from two different models from literature with appropriate modifications and improvements. The new “interacting” model is able to predict the syngas composition, input and output flow rates and the gasifier cold efficiency under different working condition and with different biomass input. It works assuming a constant biomass consumption. The results of the model has been compared to experimental data taken from a downdraft gasifier power plant system with nominal power output of 200 kWel. The plant has been set at 160 kWel in order to avoid system instabilities related to high power runs.

1. INTRODUCTION

The gasification of wood biomass is a thermo-chemical process that takes place in a reactor at a temperature ranging between 800°C and 1000°C in an under-stoichiometric atmosphere [1,2]. The gas produced by the gasification process is mainly composed of CO, CO₂, CH₄, H₂, N₂ (if the oxidizing agent is air).

Each gas volume percentage depends on various factors such as the oxidizing agent, the type and properties of biomass, the reaction conditions (temperature and pressure), the geometry of the reactor, etc. [1,2]. The gas obtained can be burned, after adequate cleaning depending on the technology, in boilers connected to ORC systems, EFGT or Stirling engine, or can be used as fuel in internal combustion engines or in high temperature fuel cells [3-8]. If the synthesis gas (called syngas) is used in an internal combustion engine, it must be adequately filtered to avoid fouling problems of the compressor and piston, in which case the stratified downdraft reactor is very suitable, since it is characterized by the production of a syngas with a low content of tars [1,2].

Figure 1 illustrates the reactor mentioned above; this figure also indicates the mass flows entering and exiting from the reactor and the layers of reaction that occur in it. Several literature papers [10-15] discuss the modeling of stratified downdraft reactors. This paper presents a working model obtained by combining two different patterns extracted from literature, making appropriate changes and additions.

The first model considered was developed by Reed and Markson [11]. It is able to estimate the length of the flaming pyrolysis layer and the length of the char reduction layer starting from the size of the gasifier and the physical properties of the biomass. That model is based on experimental correlations obtained by Huff [16].

The second model has been developed by Wang and Kinoshita [13]. The model allows to calculate the composition of the synthesis gas at the end of the flaming pyrolysis layer and the char reduction layer. It also permits to evaluate the mass or volumetric flow rate of the input air and the mass flow

rates of output char, tars and water. The model is based on the mechanism of the surface reaction of the char, on the kinetics of the reactions and on the balance equations of the molar mass in each zone.

The two models described above have been combined assuming a fixed length of the reaction zone, from which the time of char reduction has been calculated. The complete model is able to estimate the composition of synthesis gas, the input and output mass flow rates and the efficiency of gasification at different operating conditions and type of biomass assuming that the mass flow rate of biomass is a constant.

The results of the model have been validated experimentally by taking as reference a system composed of a stratified downdraft gasifier that supplies two internal combustion engines linked to two alternators. The system has a peak power of 250 kWel, but the comparison, for the purposes of validation of the model, was performed by setting the electrical output to 160 kWel to avoid instability issues.

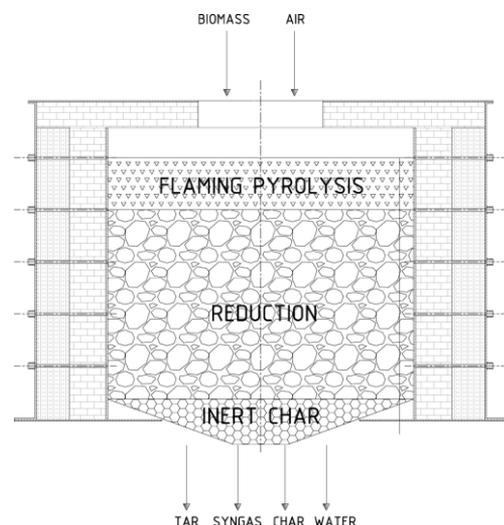


Figure 1 Stratified downdraft reactor

2. MATHEMATICAL MODELING

2.1 Reed's model

The mathematical model has been adapted from two different models taken from literature with appropriate modifications and improvements. The first model was developed by Reed and Markson [11], it predicts the flaming pyrolysis zone length l_p and the char reduction zone length l_c starting from the biomass properties and the gasifier dimensions by the following equations:

$$l_p = V_f t_p \quad (1)$$

$$l_c = V_f t_c \quad (2)$$

$$V_f = \frac{\dot{m}_{bio}(A_g F_d (1 - F_v))}{A_g} \quad (3)$$

where V_f is the fuel velocity, t_p is the pyrolysis time, t_c is the char reduction time, M is the input biomass flow, A_g is the area of the gasifier, F_d is the density of the biomass and F_v is the void fraction in the biomass. The pyrolysis time t_p has been obtained by the following equation [11]:

$$t_p = \frac{F_d V (h_p + F_m h_w)}{A q} \quad (4)$$

where V is the volume of the biomass particle, A is the surface area of the biomass particle, h_p is the heat per unit mass released by the pyrolysis process at the temperature T_s , h_w is the latent heat of vaporization of water and q is the heat transfer rate per unit area in the pyrolysis process by radiation. The values of h_p and h_w have been tabulated by Reed and Markson [4] starting from Huff data [5].

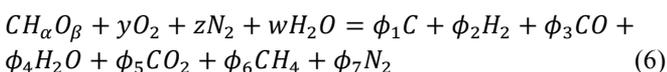
The heat transfer rate q can be obtained by a weighted average calculation from the data reported in [4], where the weight of the calculation comes from the moisture of the biomass, the surface temperature and the surface area of the biomass particle. The char reduction time has been calculated assuming a constant height H of the fixed bed from the following equation:

$$t_c = (H - l_p) / V_f \quad (5)$$

From the previous equations, it is possible to calculate the zone heights, the time of the pyrolysis process and the char reduction process assuming a constant pyrolysis surface temperature and a constant biomass consumption.

2.2 Wang's model

An additional approach, presented by Wang and Kinoshita [6], has been exploited to estimate the syngas composition, the air inlet flow, the syngas output flow and the charcoal and water production. This model does not consider the tar production, the temperature of the reduction zone and the oxidant equivalence ratio are fixed parameters. It is based on the following general reaction of gasification [13]:



where the parameters α and β can be calculated from the

ultimate analysis of the biomass normalizing with the specific weight of carbon, y and z are the molar number of the molecular hydrogen and nitrogen that they can be calculated from the reaction balance of the biomass oxidation considering the equivalence ratio ER .

This one is defined as the ratio between the air flow and the stoichiometric air flow [1]; w is the water molar evaluated from the biomass moisture F_m , ϕ_i are the molar number of the products of the gasification. The previous equation can be written in mass flow mode and it permits to calculate the syngas composition, the inlet and output flow rate assuming a constant biomass consumption. The variables ϕ_i are the unknowns of the problem.

At the end of the flaming pyrolysis zone (subscript 0) these variables have been calculated by solving the linear system below [6] assuming $\phi_{2,0} = 0$, $\phi_{3,0} = 0$ and $\phi_{7,0} = z$:

$$\phi_{1,0} + \phi_{5,0} + \phi_{6,0} = 1 \quad (7)$$

$$2\phi_{4,0} + 4\phi_{6,0} = \alpha + 2w \quad (8)$$

$$\phi_{4,0} + 2\phi_{5,0} = 2y + \beta + w \quad (9)$$

$$\phi_{4,0} = \lambda\phi_{5,0} + w \quad (10)$$

where $\lambda = 1$ is the ratio between water vapor and carbon dioxide formation [13]. In the reduction zone the temperature ranges from 1200 K to 1000 K.

Here, char is consumed gradually due to char-gas reactions and gas-gas reactions as described by the following chemical reactions [17]:

1. Boudouard reaction: $C + CO_2 \rightarrow 2CO$
2. Water-gas reaction: $C + H_2O \rightarrow H_2 + CO$
3. Methanation reaction: $C + 2H_2 \rightarrow CH_4$
4. Steam reforming reaction: $CH_4 + H_2O \rightarrow CO + 3H_2$

The surface reactions 1 and 2 involve single gas molecules, while two molecules are involved in surface reactions 3 and 4. The Langmuir-Hinshelwood mechanism [17] is applied to calculate the net rate for reactions 1 and 2 given by Eq. 10 and Eq. 11, and the Langmuir-Rideal mechanism [17] is adopted to calculate the net rate for reactions 3 and 4 given by Eq. 12 and Eq. 13.

$$v_1 = -k_{a1} \frac{\phi_5 - \phi_3^2 / (P_\phi K_{p1})}{\sum_{i=2}^7 (K_i + 1/p) \phi_i} \left(\frac{\phi_{1,0}}{\phi_i} \right)^{1/3} \left(\frac{\phi_i}{\rho d_p} \right) \quad (11)$$

$$v_2 = -k_{a2} \frac{\phi_4 - \phi_2 \phi_3 / (P_\phi K_{p2})}{\sum_{i=2}^7 (K_i + 1/p) \phi_i} \left(\frac{\phi_{1,0}}{\phi_i} \right)^{1/3} \left(\frac{\phi_i}{\rho d_p} \right) \quad (12)$$

$$v_3 = -k_{a3} \frac{\phi_2^2 - \phi_6 P_\phi / K_{p3}}{P_\phi K_{p1} \sum_{i=2}^7 (K_i + 1/p) \phi_i} \left(\frac{\phi_{1,0}}{\phi_i} \right)^{1/3} \left(\frac{\phi_i}{\rho d_p} \right) \quad (13)$$

$$v_4 = -k_{a4} \frac{\phi_4 \phi_6 - \phi_3 \phi_2^2 / (P_\phi^2 K_{p4})}{\sum_{i=2}^7 (K_i + 1/p) \phi_i} \left(\frac{\phi_{1,0}}{\phi_i} \right)^{1/3} \left(\frac{\phi_i}{\rho d_p} \right) \quad (14)$$

$$P_\phi = \frac{1}{p} \sum_{i=2}^7 \phi_i \quad (15)$$

where v_i is the net reaction, k_{ai} is the apparent rate constant, K_{pi} is the equilibrium constant and K_i is the adsorption constant for the reaction i , p is the pressure in the gasifier, P_ϕ is the pressure constant, $\phi_{1,0}$ is the initial molar number of

atomic carbon at the beginning of the reduction zone, ρ is the density of the atomic carbon, d_p is the initial equivalent diameter of the char particle.

The equilibrium constants K_{pi} have been calculated by the JANAF thermochemical tables [14] and the adsorption constants K_i have been taken from [21] both at a fixed reduction temperature T . The apparent rate constants are calculated by the following Arrhenius equation [13]:

$$k_{ai} = A_i \exp\left(\frac{-E_{ai}}{RT}\right) \quad (16)$$

where A_i is the pre-exponential factor, E_{ai} is the activation energy for reaction i , T is the reduction temperature and R is the universal gas constant. A_i and E_{ai} of each reaction have been taken from the regression analysis reported in [6]. The molar number of the products at the end of the reduction zone have been obtained integrating the following differential equations system from zero to t_c :

$$\begin{cases} \frac{d\phi_1}{dt} = v_1 + v_2 + v_3 \\ \frac{d\phi_2}{dt} = -v_2 + 2v_3 - 3v_3 \\ \frac{d\phi_3}{dt} = -2v_1 - v_2 - v_4 \\ \frac{d\phi_4}{dt} = v_2 + v_4 \\ \frac{d\phi_5}{dt} = v_1 \\ \frac{d\phi_6}{dt} = -v_3 + v_4 \end{cases} \quad (17)$$

The molar flow rate of syngas, char, and water at the end of the reduction zone have been evaluated using the molar mass of each product and assuming steady state conditions, the syngas has been considered an ideal gas and its HHV_{syngas} has been calculated using the method illustrated by Waldheim and Nilsson [18]. The tar mass flow rate has been evaluated using an energy balance:

$$\dot{m}_{tar} = \frac{HHV_{syngas} \dot{m}_{syngas} / \rho_{syngas} - \dot{V}_{syngas,exp} HHV_{syngas,exp}}{HHV_{tar,exp}} \quad (18)$$

where HHV_{syngas} is the calculated higher heating value of the syngas, \dot{m}_{syngas} is the syngas mass flow, ρ_{syngas} is the density of the syngas at normal conditions calculated considering the gas composition and the density of each component, $\dot{V}_{syngas,exp}$ is the experimental volumetric flow rate, $HHV_{syngas,exp}$ is the experimental syngas higher heating value and $HHV_{tar,exp}$ is the experimental tar heating value.

3. SIMULATION AND RESULTS

A Matlab™ software environment has been used to implement the mathematical model discussed below. The biomass adopted in this work is poplar wood-chip.

Tab. 1 collects the chemical, physical and geometrical properties of the biomass. Tab. 2 shows the model parameter adopted in the simulation, furthermore in Tab. 3 the comparison between experimental data and model output has been reported. Further details on the methodology of acquisition of experimental data and the characteristics of the system are reported in [20].

| DESCRIPTION | SYMBOL | VALUE |
|--------------------------|--------|-----------------------|
| Chip equivalent diameter | d_p | 0.0156 m |
| Biomass density | F_d | 0.4 kg/m ³ |
| Biomass void fraction | F_v | 0.63 |
| Biomass moisture | F_m | 0.03 |
| Carbon mass percentage | C | 47.7 % |
| Hydrogen mass percentage | H | 6.07 % |
| Nitrogen mass percentage | N | 46.23 % |
| Ash mass percentage | Ash | 2.75 % |

Table 1 Biomass properties

| Description | Symbol | Value |
|-------------------------------|----------|----------------------|
| Gasifier area | A_g | 0.668 m ² |
| Flaming pyrolysis temperature | T_s | 1173.5 K |
| Fixed bed height | H | 0.6 m |
| Biomass coefficient α | α | 1.52 |
| Biomass coefficient β | β | 0.67 |
| Equivalence ratio | ER | 0.3 |
| Reduction temperature | T | 1073.5 K |
| Pressure in the gasifier | p | 1 atm |

Table 2 Model parameters

| Variable | Model | Exp. | Δ |
|--------------------------------------|-------|------|----------|
| \dot{m}_{bio} [g/s] | 51.9 | 51.9 | 0 % |
| HHV_{syngas} [MJ/Nm ³] | 4.99 | 5.25 | - 5 % |
| \dot{V}_{syngas} [l/s] | 112 | 103 | + 9 % |
| \dot{m}_{char} [g/s] | 5 | 6.9 | - 27 % |
| $\dot{m}_{tar+acqua}$ [g/s] | 11.9 | 12.7 | - 6 % |
| η_{gas} | 66.5 | 66.6 | - 0.1% |

Table 3 Model output Vs. experimental data

The results shows a good correspondence of model results with the experimental data, the calculations have been made for a constant consumption of biomass equal to 51.9 g/s. The production of tar and water were added together since a high proportion of the tar remain suspended in the output water so to avoid to separate the two phases was considered the cumulative figure.

However, there is a maximum error of 27% related to the production of char (char in practice it is mixed with the ashes and then the data is not very reliable), while for the other variables the error is lower. On average, the difference between model data and experimental results is about 9%, a good result considering the errors in the acquisition of experimental data and the assumptions of quasi stationary conditions adopted in the model.

4. CONCLUSIONS

In the present study, a stratified downdraft gasifier working with wood biomass has been modeled. Two sub-models have been chosen from literature; the sub-models have been linked together to form a single computer code that it allows to provide the behavior of the main operating variables of the reactor.

The model validation has been performed considering the experimental data taken from an existing installation with a maximum power of 250 kWel. The error between the outputs of the model and the experimental data has been chosen to validate the code: the maximum error found is 27% while the average error is 9%.

The developed model simulates the operation of the reactor varying the characteristic parameters of the biomass and the geometric parameters and performance of the reactor itself.

A further validation varying these parameters may indicate the range of applicability of the model in which the model fits with good agreement the experimental data. From this analysis, further information to optimize the operation of the reactor should be found.

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REFERENCES

1. T.B. Reed, A. Das, Handbook of Biomass Downdraft Gasifier Engine Systems. U.S. Department of Energy: Solar Energy Research Institute, 1988.
2. FAO, Wood gas as engine fuel, Rome: Publication Division, *Food and Agriculture of the United Nations*, ISBN 92-5-102436-7, 1986.
3. G. Galeno, Modellizzazione di un micro cogeneratore basato sulla tecnologia MCFC accoppiata ad un gassificatore di biomassa, Ph.D. thesis Università degli Studi di Napoli Federico II, 2007.
4. A. Duvia, M. Gaia, Cogenerazione a biomassa mediante Turbogeneratori ORC Turboden: tecnologia, efficienza, esperienze pratiche ed economia. *Energia prodotta dagli scarti del legno: opportunità di cogenerazione nel distretto mobile*, 11 novembre 2004.
5. F. Martelli et al., Technical study and environmental impact of an external fired gas turbine power plant fed by solid fuel. *Proc. 1st World Conference of Biomass*, Sevilla 2000.
6. V. Naso, La macchina di Stirling. CEA, 1991.
7. C. Souleymane, Motori a combustione interna e turbine a gas di piccola taglia per gas di sintesi. Bachelor thesis Università degli Studi di Padova, 2011-2012.

8. F. Marini, Monitoraggio e valutazione delle prestazioni di un impianto di cogenerazione a cippato di legno con gassificatore e motore Stirling, Centro Cisa website: <http://www.centrocisa.it/ImpiantiRealizzati/stirlingCastelDaiano.php> [25/04/2012].
9. M.P. Arnavat, J.C. Bruno, A. Coronas, Review and analysis of biomass gasification models, *Renewable and Sustainable Energy Reviews*, vol. 14 (2010), pa. 2841-2851.
10. T.B. Reed, M.L. Markson, A predictive model for stratified downdraft gasifier, *Progress in Biomass Conversion*, vol. 4 (1983), pag. 219-254.
11. T.B. Reed, B. Levie, A simplified model of the stratified downdraft gasifier, *International Bio-Energy Directory and Handbook* (1984), pag. 379-389.
12. T.B. Reed, B. Levie, M.L. Markson, M.S. Graboski, A mathematical model for stratified downdraft gasifier, *Symposium on Mathematical Modeling of Biomass Pyrolysis Phenomena*, 1983.
13. Y. Wang, C.M. Kinoshita, Kinetic model of biomass gasification, *Solar Energy*, vol. 51 (1993), pag.19-25.
14. A.Kr. Sharma, Equilibrium modeling of global reduction reactions for a downdraft (biomass) gasifier, *Energy Conversion and Management*, vol. 49 (2008), pag. 832-842.
15. A.Kr. Sharma, Modeling and simulation of a downdraft biomass gasifier 1. Model development and validation, *Energy Conversion and Management*, vol. 52 (2011), pag. 1386-1396.
16. E.R. Huff, Effect of size, shape, density, moisture and furnace wall temperature on burning time of wood pieces. In: *Fundamentals of thermochemical biomass conversion: An International conference*, Estes Park, CO; 1982.
17. K.J. Laidler, Chemical kinetics. Harper & Row Publishers, New York; 1987.
18. L. Waldheim, T. Nilsson, Heating value of gases from biomass gasification. Report prepared for: IEA Bioenergy Agreement, Task 20 – Thermal Gasification of Biomass, 2001.
19. S.A. Channiwala, P.P. Parikh, A unified correlation estimating HHV of solid, liquid and gaseous fuels, *Fuel*, vol. 81 (2002), pag.1051-1063.
20. G. Allesina, C. Cattini, S. Pedrazzi, P. Tartarini. Sperimentazione di metodi non invasivi per il monitoraggio di un impianto di gassificazione a biomasse legnose, *La Termotecnica*, marzo 2012.
21. R.C. Everson, H.W.J.P. Neomagus, H. Kasaini, D. Njapha, Reaction kinetics of pulverized coal-chars derived from inertinite-rich coal discards: Gasification with carbon dioxide and steam, *Fuel*, vol. 85 (2006), pag. 1076-82.