CHEMICAL ENGINEERING TRANSACTIONS

VOL. 37, 2014

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Eliseo Ranzi, Katharina Kohse- Höinghaus

ISBN 978-88-95608-28-0; **ISSN** 2283-9216

DOI: 10.3303/CET1437058

Modeling of Syngas Production from Biomass Energy Resources Available in Taiwan

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Present work is aimed at developing a model for biomass gasification in a system into exercise in Taiwan. The treated biomass, or refuse derived fuel from biomass (RDF), is preliminary experimentally characterized in an electro-thermal furnace in terms of proximate and ultimate analysis. The lower heating value is then determined. The gasification model, although simple, allows evaluating the optimal control strategy for the production of the syngas of highest quality. A sensitivity analysis is also performed to highlight the effects of the initial moisture content on the gasification temperature and syngas composition.

1. Introduction

In recent years, the research of new energy sources has become of primary importance in every industrialized area of the world. One of the technologies representing a valuable alternative to energy conversion systems employing fossil fuel is biomass gasification with successive combustion of the released syngas. Gasification is defined as the thermo-chemical conversion of a carbonaceous solid fuel in a gaseous fuel (McKendry, 2002). This last can be used in a wide range of applications (direct heating, co-generation, or feedstock for green chemistry or for biodiesel production) (Deydier et al., 2011). The advantages of using biomass energy sources mainly lie in their wide availability and in the lower level of pollutants released during their utilization. Main components of syngas are CH_4, H_2, CO, CO_2, H_2O and N_2 (Hindsgaul et al., 2000), but a variety of tars are also produced during the gasification reaction.
The processes occurring in a gasification plant can be numerically modelled in order to obtain information about the syngas composition, gasification temperature and pollutants formation. Numerical modelling offers the great advantage of being applied directly at the industrial scale of interest, thus avoiding the need to resort to scaling-up of results deriving from lab-scale experiments. This is very significant for studying combustion processes, for which scale-up procedures are generally complicated by the strong interaction between turbulence, reaction kinetics, heat release and radiation.
Many authors have studied gasification processes using numerical tools. Jarungthammachote and Dutta (2007) developed an equilibrium model for predicting the composition of the syngas released in a downdraft gasifier. Babu and Sheth (2004) investigated the effects of operating parameters as the oxygen enrichment or the preheating of air on the gas composition. Ptasinsky et al. (2007) compared different types of biofuels for their gasification efficiency and benchmarked this against gasification of coal. Barman et al. (2012) developed an equilibrium model of gasification in a fixed bed downdraft gasifier including tars. Deydier et al. (2011) presented a model describing a gasification process composed of a dryer section and a gasification section for a travelling bed gasifier.
Present work aims at developing a simulation model for the gasification process taking place in a system into exercise in Taiwan, fed with two kinds of biomasses largely available in that country, as rice husk and biosludge. The model allows optimizing the system control parameters during its real operation.

Please cite this article as: Costa M., Massarotti N., Cappuccio G., Chang C.T., Shiue A., Lin C.J., Wang Y.T., 2014, Modeling of syngas production from biomass energy resources available in taiwan, Chemical Engineering Transactions, 37, 343-348
DOI: 10.3303/CET1437058

2. Gasification system and biomass characterization

The gasification system considered in this study is a typical downdraft gasifier, whose scheme is reported in Figure 1. The biomasses used in the plant are of two kinds: rice husk and biosludge. An idea of the performances of different technologies for power generation from rice husk is given in the paper by Prasara-A et al. (2012). Biosludge produced just in Taiwan from the biological decomposition of organic discharges from food processing (milk-derivative), wine (beer) brewery and livestock (swine) farms in secondary wastewater treatment systems is deeply characterised by Tsai (2012).
The biomasses here considered are analysed by following the methods issued by the Environmental Protection Administration, China (Gui-Bing Hong et al., 2012). The obtained proximate and ultimate analyses are presented in Table 1 and Table 2. Since percentages of S and Cl in the biomasses are very small (<1%), they are neglected in this study. The not negligible content of nitrogen in the biomasses, especially in the biosludge, is considered as contributing to the N_2 amount in the syngas, without considering different routes towards nitrogen compounds formation, as HCH. This assumption derives from the need to maintain the chemical kinetics of the numerical model of low complexity.

Table 1. Proximate analysis of biomass used in Taiwan.

Proximate analysis	Moisture	Volatile Matter	Inorganic Matter	Char
Rice husk	4%	68%	24%	4%
Biosludge	5%	45%	40%	10%

Table 2 Ultimate analysis of biomass used in Taiwan.

Ultimate analysis	C	H	O	N	S	Cl
Rice husk	70%	15%	10%	5%	0%	0%
Biosludge	65%	15%	10%	10%	0%	0%

Lower heating value (LHV) is calculated through the correlation by Channiwala and Parikh (2002):

$$HHV = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.0151N - 0.0211Ash \quad (1)$$

$$LHV = HHV - 9m_H h_{fg} \quad (2)$$

where C, H, S, O, N and Ash are percentages of mass of carbon, hydrogen, oxygen, nitrogen, sulfur and ash in the dry solid fuel, m_H is mass fraction of hydrogen in solid fuel and h_{fg} is enthalpy of vaporization of water (2.272 MJ/kg). The resulting LHV is equal to 18.78 MJ/kg for rice husk, 11.69 MJ/kg for biosludge.

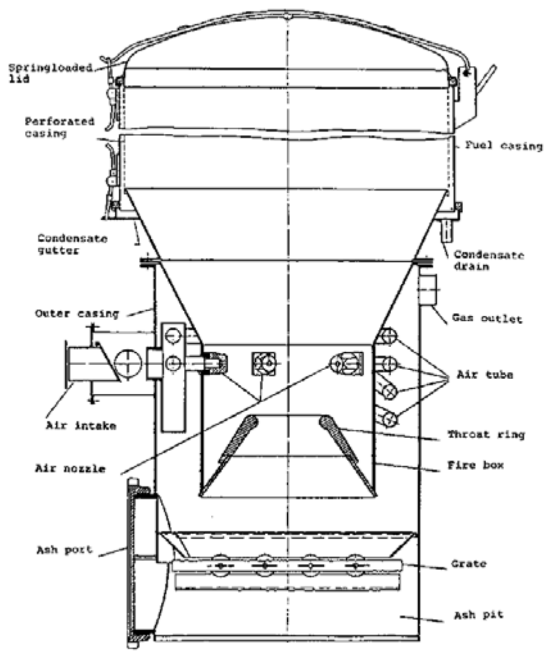

Figure 1. Scheme of the downdraft gasifier used in Taiwan.

3. Mathematical model

Contrary to a technically mature design of present day gasification plants, that combines high thermal efficiency with low pollutants emissions, the commonly used control strategies are obsolete when compared with the possibilities of modern control theory. Existing models are often too complex to be used within model based control strategies. It is instead important to emphasize the need for simple models. The model complexity must be intended as being just to the point necessary to achieve a reasonable representation of the corresponding equipment and allowing its design and control. Too simple models normally provide only superficial information, while too complex models may take years to develop and often involves considerable computational difficulties due to convergence problems or inconsistencies. Following the classification of De Souza Santos (2004), the problem of solid bed conversion may be approached by developing phenomenological models based on the solution of fundamental equations, such as the laws of thermodynamics (laws of mass, energy, and momentum conservation), and constitutive equations, or by analogy models (empirical or semi-empirical) that mimic the behaviour of the fundamental aspect of the process. The phenomenological models may be further classified on the ground of the level of assumed simplification, starting from zero dimensional time independent schematizations (0D-S or 0D steady models), based on the thermo-chemical equilibrium assumption between participating species at the gasification temperature, to reach 3D dynamic models (3D-D or 3D dynamic models) accounting for both the spatial and temporal dependence of the relevant variables. The here presented model is developed on the ground of the reasoning by Jarungthammachote and Dutta (2007). It is a 0D-S model, where the gasifier is considered as a closed system in which the biomass reacts with air to produce syngas. The model is based on the hypothesis of thermo-chemical equilibrium between the species involved in the following reaction:

$$CH_xO_yN_z + wH_2O + m(O_2 + 3.76N_2) \\ \rightarrow n_{H_2}H_2 + n_{CO}CO + n_{CO_2}CO_2 + n_{H_2O}H_2O + n_{CH_4}CH_4 + \left(\frac{z}{2} + 3.76\,m\right)N_2. \tag{3}$$

In Eq. (3), $CH_xO_yN_z$ is the chemical formula of the organic part of the biomass; w is the amount of moisture in the biomass (moles of H_2O per mole of $CH_xO_yN_z$), and m is the amount of reacting oxygen (moles of O_2 per mole of $CH_xO_yN_z$). On the right hand side of Eq. (3), n_i are the numbers of moles of the species i in the syngas. In order to determine the syngas composition, the following equations are written:

Carbon C:

$$n_{CO} + n_{CO2} + n_{CH_4} - 1 = 0 \tag{4}$$

Hydrogen H:

$$2n_{H_2} + 2n_{H_2O} + 4n_{CH_4} - x - 2w = 0 \tag{5}$$

Oxigen O:

$$n_{CO} + 2n_{CO_2} + n_{H_2O} - y - w - 2m = 0 \tag{6}$$

The thermo-chemical equilibrium of the following reactions is assumed:

$$\mathrm{CO} + \mathrm{H_20} \leftrightarrow \mathrm{CO_2} + \mathrm{H_2} \tag{7}$$

$$\mathrm{C(s)} + 2\mathrm{H_2} \leftrightarrow \mathrm{CH_4}, \tag{8}$$

which can be written as:

$$K_1 n_{CO} n_{H_2O} - n_{CO2} n_{H_2} = 0 \tag{9}$$

$$K_2 {n_{H_2}}^2 - n_{CH_4} n_{tot} = 0. \tag{10}$$

The energy balance, needed to evaluate the gasification temperature, is here modified with respect to the original model in order to account for the actual initial temperature, T_{in}, and the enthalpy of the inorganic matter, computed by employing the value of the specific heat $c_{p,ino}$=1 kJ/kg (Deydier, 2011) (the enthalpy of the inorganic matter at the reference temperature T_{ref} is null):

$$\sum_{k=reac} n_k h_{f_k}^0 (T_{ref}) + \sum_{j=reac} n_j a_j T_{in} + \sum_{j=reac} n_j b_j T_{in}{}^2 + \sum_{j=reac} n_j c_j T_{in}{}^3 + \sum_{j=reac} n_j d_j T_{in}{}^4 + \dot{m}_{ino} c_{p,ino} (T_{in} - T_{ref}) = \sum_{j=prod} n_j h_{f_j}^0 (T_{ref}) + \sum_{j=prod} n_j a_j T + \sum_{j=prod} n_j b_j T^2 + \sum_{j=prod} n_j c_j T^3 + \sum_{j=prod} n_j d_j T^4 + \sum_{j=prod} n_j k_j + \dot{m}_{ino} c_{p,ino} (T - T_{ref}) \quad (11)$$

where h_f^0 is the molar enthalpy of formation, a, b, c and d are the coefficients of the empirical correlation assumed for the specific heat and k is an integration constant for each species. Model validation, here not described, is performed for one of the biomasses considered by Jarungthammachote and Dutta (2007).

4. Results and discussion

The model described in the previous section is applied to define the optimal design point of the system schematized in Figure 1. The quality of the gasification process is estimated by calculating the LHV of the syngas with the contributions of CH_4, CO and H_2. The composition of the released syngas, the resulting LHV and the gasification temperature are analysed as the amount of the gasifying agent is changed. Figure 2 reports the syngas composition for the two biomasses for T_{in} = 373K as a function of the coefficient m. This last is varied up to the 90% of the stoichiometric value. One may note that the CH_4 formation decreases with m in both the cases, while the formation of H_2 reaches a maximum for values that differs for the two biomasses. For rice husk the H_2 mass fraction reaches the maximum for m = 1.15. For the biosludge, the maximum value is attained for m = 1.42. The higher N_2 mass fraction consequent the thermal treatment of the biosludge is also evident.

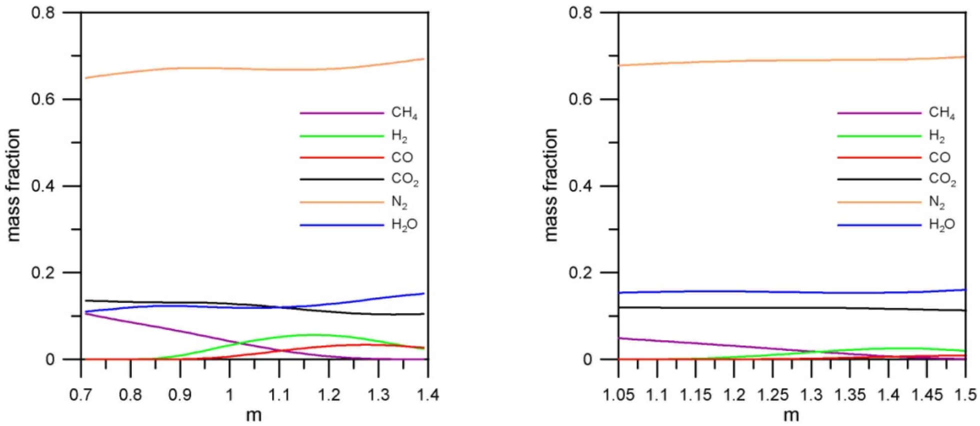

Figure 2. Syngas composition for rice husk (left) and biosludge (right) as a function of the oxygen amount.

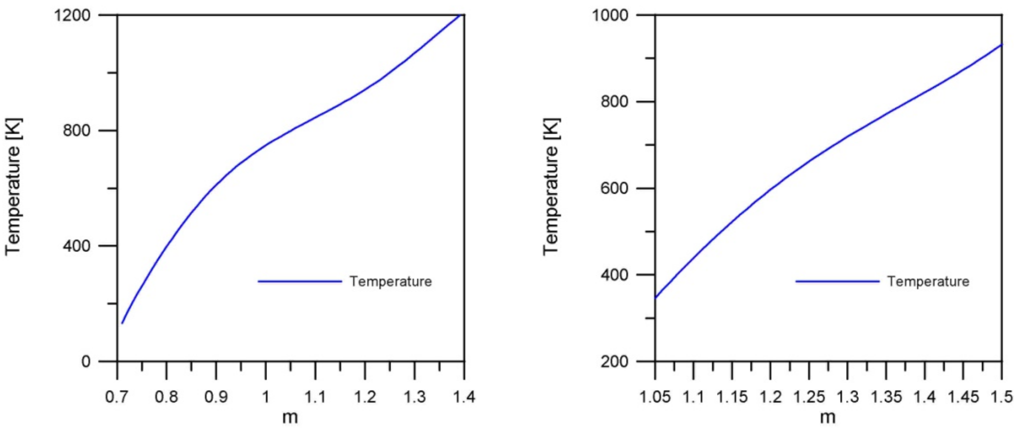

Figure 3. Gasification temperature for rice husk (left) and biosludge (right) as a function of the oxygen amount.

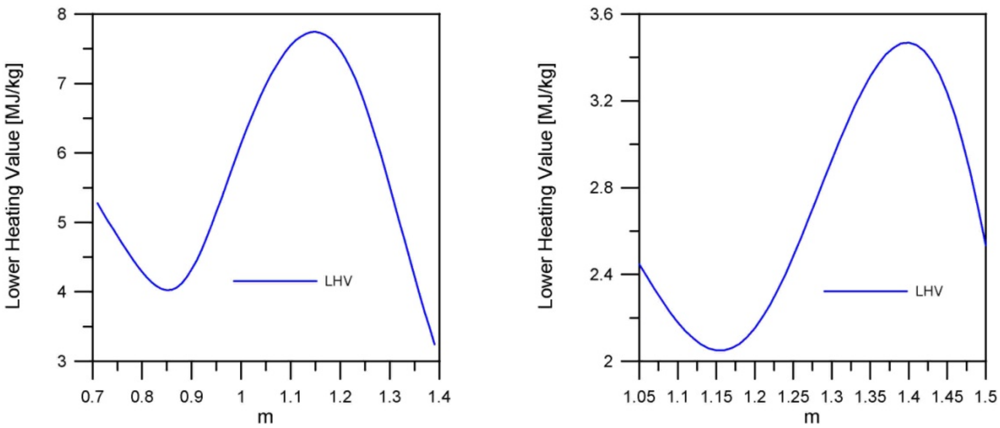

Figure 4. Syngas LHV for rice husk (left) and biosludge (right) as a function of the oxygen amount.

Figure 3 shows the gasification temperature for rice husk and biosludge. Figure 4 shows the lower heating value (LHV) of the released syngas. The LHV of the rice husk derived syngas reaches the maximum value of 7.74 MJ/kg for m = 1.15, whereas the LHV of the biosludge derived syngas reaches its maximum value of 3.47 MJ/kg for m = 1.4. Since the target is the maximization of the LHV, these two points can be regarded as those of optimal design of the system to derive the amount of needed oxygen (and air) for an assigned biomass amount.

Once the optimal equivalence ratio of the gasifier is chosen, one may examine the effect of a variation in the initial moisture content of the biomass. Figure 5 and 6, report, respectively, the gasification temperature and the released syngas LHV for rice husk and biosludge.

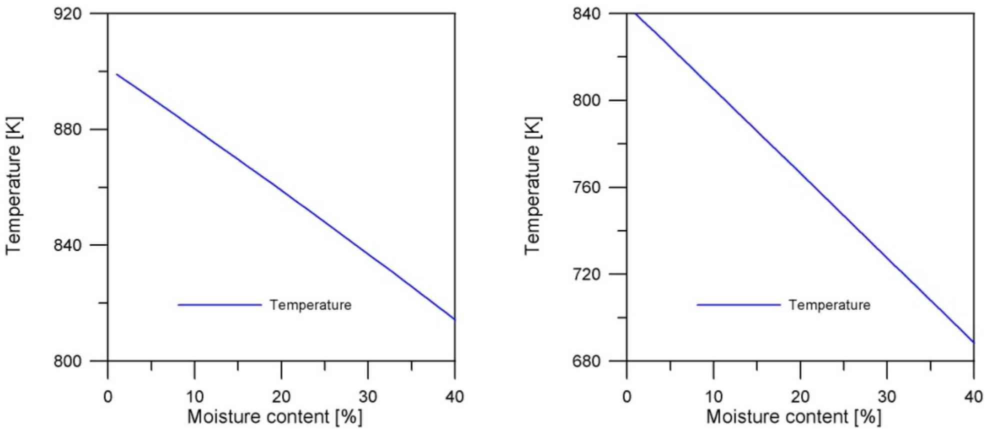

Figure 5. Effects of moisture content on gasification temperature for rice husk (left) and biosludge (right).

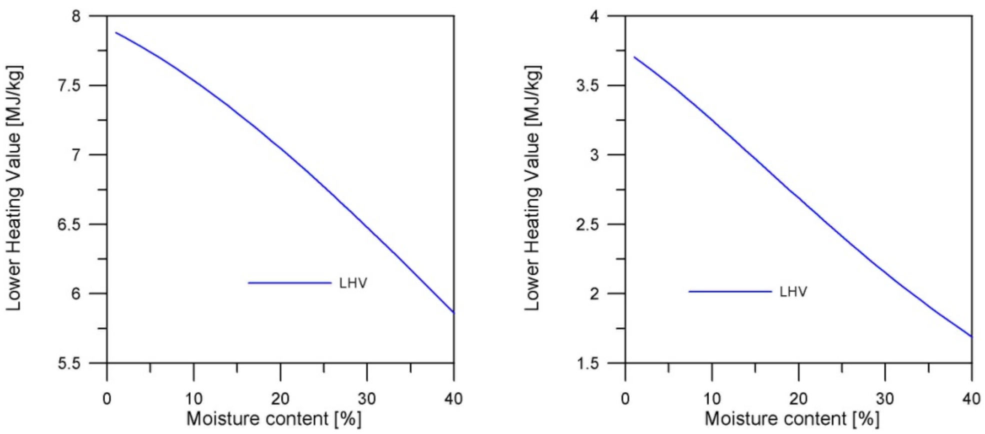

Figure 6. Effects of moisture content on the syngas LHV for rice husk (left) and biosludge (right).

As the initial moisture content increases, hence as the parameter w of reaction 3 increases, the model predicts a decrease in the gasification temperature and a change in the syngas composition, here not reported for the sake of brevity, which reflects in lower values of LHV. This constitute a further confirmation of the validity of the model in describing the main physical and chemical phenomena occurring in a gasification process, although an high level of simplification is adopted.
The model of the downdraft gasifier here introduced proves being suitable to be used for control purposes or within optimization procedure even of multi-objective kind.

5. Conclusions

A zero-dimensional steady model is used to characterize the gasification process of two different biomasses (rice husk and biosludge) in a downdraft gasifier into exercise in Taiwan.
The treated biomasses are of great interest in that country due to the typical employment of rice in the Taiwanese alimentation as well as to the large availability of sludge.
The here presented model considers a closed system and the thermo-chemical equilibrium between the involved species. A parametric analysis of the released syngas composition, temperature and LHV as a function of the gasifying amount allows determining the optimal design points of the considered system for both the biomasses. These slightly differ one from each other.
The effect of the initial moisture content of the biomasses is also analysed.
Results demonstrate that the gasification model can be used within model based control strategies for the highest quality of the released syngas.

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