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Experimental and modeling analysis of Air and CO₂ biomass gasification in a reverse lab scale downdraft gasifier

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Abstract

This research work aims at investigating the effect of carbon dioxide feed in biomass gasification as a possible way to directly exploit the exhaust gas from the engine of combined heat and power systems to convert carbon dioxide to carbon monoxide via Boudouard reaction and consequently increase the carbon conversion and reduce char yield. The effects on biomass gasification using air, and air diluted with carbon dioxide were assessed in a reverse downdraft lab-scale gasifier utilizing 2 kg of pelletized biomass. This reactor is mounted on a digital weighing balance which enables the recording of mass loss during the gasification process. Furthermore, the mixture of air and CO₂ is obtained from two mass flow controllers which enable constant and desired flux of gasifying agents across the gasifier.

At the same time, an in-house developed thermodynamic equilibrium model was applied to predict the gas composition and char output. Unlike the classical equilibrium strategy that calculates the gasification products using the Gibbs energy minimization method at fixed temperature and pressure, the current approach is based on the enthalpy of the reactants, analogous to the adiabatic combustion temperature. Also, a correction factor accounting for the heat losses, was implemented. The model outcome shows a good agreement with the experimental results, especially in terms of predicted char yields and trends of the dominant producer gas species. The same strategy was used to describe the behavior of the gasification system and estimate the quality of producer gas and the cold gas efficiency of the system.

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1. Introduction

Exhaustive efforts and innumerable approaches to curtail CO₂ discharge into the atmosphere have brought forward wide class of technologies related to CO₂ separation, storage and more recently the conversion of CO₂ into useful chemicals and fuels [1]. Biomass gasification, in current times, has played a crucial role in curtailing CO₂ emissions from power sector. The investigations related to reaction of char and CO₂ have created interests into CO₂ gasification of biomass. Considering the fact that CO₂ capture itself amounts to huge fractions of carbon capture and storage costs [2], burying it in deep in geological storage sites is meaningless, especially if CO₂ can be converted into useful chemicals.

This work deals with the study of dilution of air with CO₂ in the course of biomass gasification using a peculiar reactor placed on a digital balance. All the fluxes including the biomass weight loss was recorded and knowing both the biomass and producer gas composition the mass balance was closed.

1. Materials and methods

The feedstock used during the experimental campaign was wood pellet (6 mm diameter) made from coniferous tree. The biomass was analyzed in order to characterize it in terms of moisture content (EN ISO 18134-2:2015), ash content (UNI EN 14775:2010), elemental composition (UNI EN ISO 16948:2015) and caloric value (UNI EN 14918:2010). Each analysis was repeated at least three times. Biomass moisture was determined for each gasification test. The average values are shown in Table 1. The moisture of biomass presents a variation between 8.3 wt.% and 6.5 wt.% referred to kg of biomass wet. The biomass calorific value is expressed as lower calorific value (LHV).

Table 1. Biomass characterization (*by difference).

Lab analysis	Moisture (wt.% w.b)	Ash (wt.%d.b)	C (wt.%d.b)	H (wt.%d.b)	N (wt.%d.b)	S (wt.%d.b)	O* (wt.%d.b)	LHV (MJ/kg d.b)
pellet	7.1	0.28	49.79	5.55	0.10	0.38	43.91	16.89

2.1. Experimental set-up

The gasification reactor is a stainless cylinder vessel with an internal diameter of 0.056 m per 1.15 m height. The reactor is isolated by a glass-wool layer of 0.05 m thickness, it is closed at the bottom with a flange and opened on the top. The top part of the reactor is configured as a burner [3]. In fact, the producer gas is burned on the top of the reactor and a probe for gas analysis is arranged 0.1 m above the flame in order to avoid air infiltration (Fig. 1).

The reactor configuration is a reverse downdraft gasifier, the gasifying agent flow from the bottom to the top, in contrast the reaction flame zone moves in the opposite direction (from the top to the bottom).

A fabric filter, four impinger bottles and a filter made by silica gel compose the producer gas cleaning system. Then the cleaned gas is analyzing by a portable gas chromatograph (microGC 490 Agilent, SRA instruments) able to detect H₂, O₂, N₂, CH₄, CO and CO₂.

The gasification reactor is placed on a digital weight balance in order to record the total weight every 3 seconds. Therefore, the loss of mass could be monitored continuously during the test. In addition, the mass flow (MF) rate of air and carbon dioxide and the temperatures inside (TI) and on the external wall (TE) of the reactor are monitored and recorded using a control and data acquisition unit (SCADA) based on LabVIEW (Fig. 1).

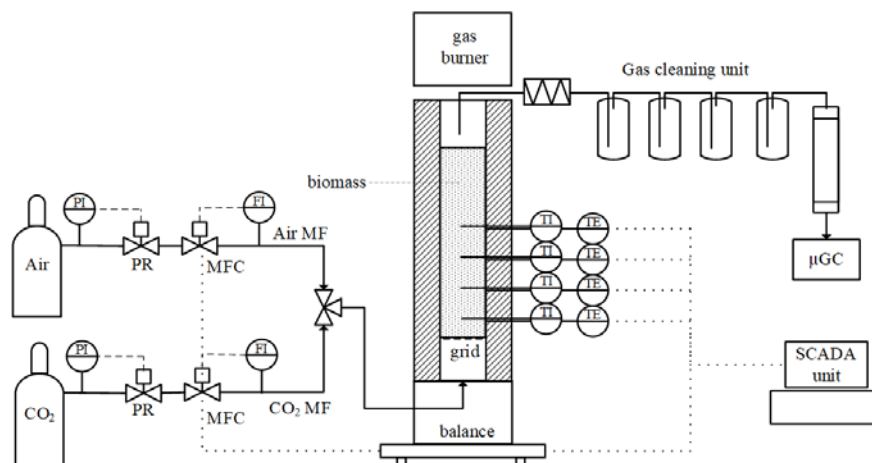


Fig. 1. Experimental set-up scheme

2.2. Experimental methodology

Experimental tests were carried out in order to obtain both a constant production in terms of gas flow rate and gas composition. For these reasons, after a warm-up phase using only air, air and CO₂ flow rates were kept constant. After several tests for investigating the reactor behavior, a range of gasifying agent flows were identified in order to obtain a producer gas with a sufficient calorific value to sustain the burning on the top (outside the reactor) and at the same time, to get no movement of particles outside the system. In this way, the weight monitored during the tests correspond exactly at the mass loss due the gasification process. Gasification experiments utilized approximately 2 kg of biomass for each test.

Three cases are chosen in order to compare biomass gasification with air and with air added of carbon dioxide. Case A: air gasification at different flow rates. Case B: fixed air flow rate and different CO₂ flow rates. Case C: fixed CO₂/N₂ ratio in the gasifying agent at different flow rates (Table 2).

Table 2. Gasifying agent: air and carbon dioxide flow rate, CO₂/N₂ ratio and equivalent ratio (E.R.) divided by test.

Case	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3
Air (NLPM)	19.0	17.5	15.1	13.5	15.0	15.0	15.0	15.1	17.7	15.0	13.6
CO ₂ (NPPM)	0.0	0.0	0.0	0.0	1.2	2.0	2.4	3.0	2.8	2.4	2.2
CO ₂ /N ₂ (-)	0.0	0.0	0.0	0.0	0.10	0.17	0.20	0.25	0.20	0.20	0.20
E.R. (-)	0.368	0.337	0.322	0.301	0.378	0.406	0.414	0.448	0.484	0.414	0.395

2.3. Thermodynamic model approach

The applied model is based on the method of Gibbs energy minimization. Baratieri et al. [4] developed a model following this formulation using the Cantera software library [5]. The solver implemented in Cantera is a version of the Villars–Cruise–Smith (VCS) algorithm [6]. The NASA [7] and the GRI-Mech [6] databases was used to evaluate the thermodynamic properties of the chemical species taken in to account in the model. A two-phase formulation of the model was used and sixty-one chemical species were considered for the calculation of the equilibrium composition of the reaction products: 60 in the gaseous phase and 1 in the solid phase (graphite, the carbon allotropic form). The calculated yield of solid carbon from the model can be used as an estimate of the actual charcoal residue of the gasification process, while the gaseous products for an evaluation of the producer gas.

In the standard gas-solid formulation [8] the temperature of the process should be provided for the assessment of the equilibrium composition. In this work, a different approach based on the concept of adiabatic gasification temperature is used. The adiabatic gasification temperature is defined similarly to the concept of adiabatic flame

temperature used in the combustion process. The adiabatic temperature in both cases is defined as the temperature at which the products have the same enthalpy of the reactants. In gasification process, the reactants are not completely oxidized and are converted into combustible products. Therefore, the enthalpy gap between the reactants and the products (at the reactants temperature) is given by the difference between the total energy that can be potentially released by the reactants (biomass and gasifying agent) and the energy still stored into the solid residue (char) and the chemical bounds of the combustible species composing the producer gas. In order to estimate the adiabatic gasification temperature, an iterative calculation is used taking into account all the enthalpy contributions described before.

In addition, a calibration parameter can be applied, decreasing the enthalpy gap between the reactants and the products in order to take into consideration the presence of heat losses in the system. The simplest way to determine the correction factor is to find through an iterative process the value that minimizes the error between the experimental and the model results in terms of gas composition and char yield. The estimated value is considered as a characteristic parameter of the system.

For each performed test, the average values of all the parameters are evaluated in a range where all the monitored variables in terms of mass loss, gas composition and temperature profile are in steady state. Knowing the consumption of biomass, the gasifying agent flow rate, the biomass and gas composition, the mass balance can be closed in order to estimate all the relevant gasification parameter.

The calibration of the model is carried out for each test using a code that compares the experimental data in terms of gas composition and char yield to the model results. The calibration parameter is expressed in terms of energy per kg of biomass and can be interpreted as a parameter that takes into account all the heat losses in the system. This parameter is named “ ΔH calibration”.

2.4. Results and discussion

In Fig. 2, the values of ΔH that minimizes the sum of the errors for all the investigated parameters (all the species in the producer gas and the char yield), are represented as a function of the equivalent ratio (ER). This parameter represents the ratio between the actual oxygen supplied to the process and the oxygen required for a stoichiometric combustion.

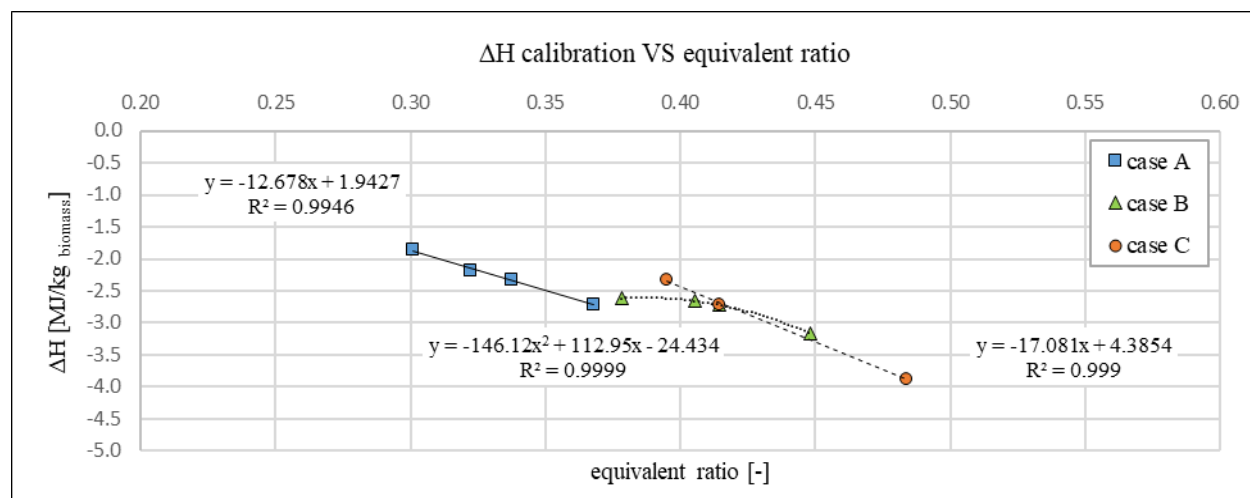


Fig. 2. Model calibration analysis.

A good correlation can be recognized between the ΔH calibration and the equivalent ratio. In particular, in case A and C a linear trend gives a r-square close to one, in case B a conic function fits better.

The comparison between experimental data and model results is presented in Fig. 3. For each test, the ΔH calibration value is calculated using the functions presented before and the equivalent ratio from experimental data.

In this way, the only parameters of input for the model are the equivalent ratio, the biomass and gasifying agent composition and their mass fluxes.

There is a clear trend of some parameters in function of the equivalent ratio (e.g., methane and char); increasing the equivalent ratio, the fraction of methane and the char yield decrease. In contrast, some trends are related to the used gasifying agent. For instance, in air gasification (case A), in the range of measurement, the hydrogen and the carbon monoxide, show similar trends; they increase at the growing of the equivalent ratio.

The carbon dioxide has instead an opposite trend. In the case of air and CO₂ gasification (case B and C) a similar tendency can be recognized for carbon monoxide, hydrogen, nitrogen and methane. On the contrary, at constant CO₂/N₂ (case C), carbon dioxide and char yield show different trends with respect to case B. In the range of study, it is quite clear that the use of air and CO₂ increase the conversion of carbon; in fact, char consumption increases adding CO₂ to the air flow rate in both case B and C.

Considering the model results, it should be noted that there is a good agreement between the experimental data and the model results in terms of char production. This is related to the fact that, in the methodology used for the estimation of ΔH calibration, the error of char represents a consistent part of the total error considering all the studied parameters.

In both the cases B and C, the trends of methane, hydrogen and nitrogen are well described, even if the experimental values are underestimated concerning methane and overestimated concerning hydrogen. Comparing the trends of the model results and the experimental data for case A, they are in the opposite direction for hydrogen. Moreover, there is an underestimation of carbon dioxide and an overestimation of carbon monoxide and nitrogen.

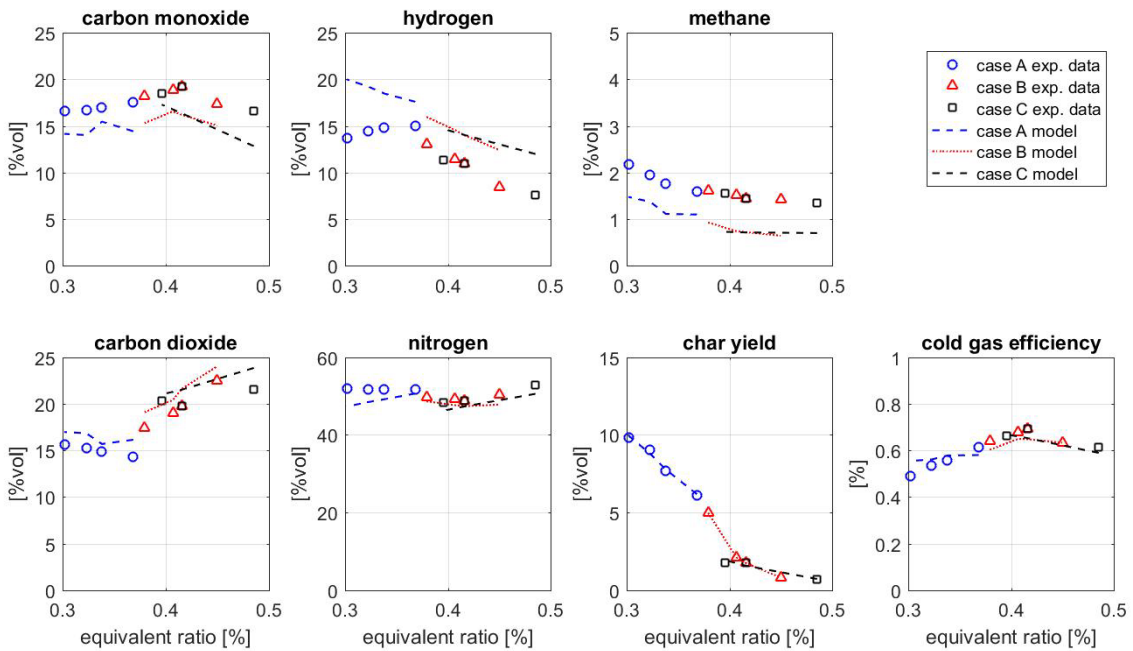


Fig. 3. Comparison between model and experiment data.

On the energy efficiency side, in gasification process usually a parameter named "cold gas efficiency" is used in order to consider the ratio between the energy in input into the system provide with the biomass and the energy generated in terms of producer gas, quantified considering the flow rates and their respective calorific values. In this case, there is a good fitting between the model and the experimental data. In the range of investigated gasifying agent flow rate, the maximum value of cold gas efficiency is achieved using air and CO₂ as gasifying agent.

2.5. Conclusions

A general analysis of biomass gasification is carried out using air and air added with CO₂ in a reverse downdraft gasifier. After an experimental campaign, a thermodynamic model is developed in order to compare the experimental and model results. A different approach is carried out in terms of thermodynamic equilibrium model. In this approach, the adiabatic gasification temperature (defined in analogy of the adiabatic combustion temperature) is found out starting from the reactants enthalpy. In addition, a correction factor taking into account the heat losses in the system is calibrated through the minimization of the error between experimental and model data.

The results are shown in relation with the equivalence ratio. It should be noted the same trend between the char and methane increasing the equivalent ratio. In both case their values decrease independently using air or air adding CO₂. However, using air and CO₂, higher cold gas efficiency can be reached due to the higher char conversion (in the range of investigation). Therefore, the addition of carbon dioxide as gasifying agent in the biomass gasification process can enhance the carbon conversion.

In general, the outputs of the model developed for this work present an overestimation of hydrogen and a slight overestimation of carbon dioxide and nitrogen using only air as gasifying agent (case A). In contrast, carbon monoxide and methane are underestimated. A positive aspect of this work is that the trends of producer gas in terms of composition (except for hydrogen in the case of air gasification) are in quite good agreement with the trends found out from the experimental measures. This aspect is quite relevant for example in the control and automation of the systems, when the trends are more important than the actual values for developing predictive algorithms (i.e. in the model-based strategy control [9]). Moreover, this model approach could be useful if the temperature inside the reactor is unknown or difficult to be measured, as in the case of small gasification CHP units. A simple thermodynamic equilibrium model as the one presented in this work can be used in order to manage the behavior of the reactor knowing the characteristics of biomass and monitoring the reactants flow rates both in terms of biomass and gasifying agent.

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