Biomass gasification process in a downdraft fixed bed gasifier: a real time diagnosis model based on gas composition analysis

Gasificación de biomasa en un reactor de lecho fijo en equicorriente: un modelo de diagnóstico en tiempo real a partir de la composición del gas pobre

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Abstract

This article is focused on the diagnostic technique used in the Thermal Engines Laboratory of the University of Valladolid (Spain), to perform real time calculation, monitoring and recording of gasification physical variables, only from gas composition analysis and some other measurements such as local temperatures and gas flow rate. By assuming some simplifying hypothesis it is possible to calculate the main gasification parameters such as biomass consumption, air/fuel ratio, thermal efficiency, and generated thermal power. The aim of this work is to explain the technique implemented and to give an idea of the wide range of applications that it can have, underlining its simplicity, its reliability and the low costs of the equipment needed.

-----*Keywords*: Biomass gasification, monitoring, diagnosis, gas composition, process control.

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Resumen

Este artículo se centra en la técnica de diagnóstico utilizada en el Laboratorio de Máquinas y Motores Térmicos de la Universidad de Valladolid (España) en una planta piloto de gasificación de biomasa, con el fin de monitorear y almacenar las variables calculadas en tiempo real y de esta manera caracterizar el proceso. Esta técnica se desarrolla mediante el análisis de la composición del gas pobre y otras mediciones, tales como temperaturas locales y el flujo másico del gas pobre. Asumiendo algunas hipótesis simplificadas es posible calcular los principales parámetros que caracterizan la gasificación, tales como tasa de consumo de biomasa, dosado relativo de gasificación, eficiencia térmica, potencia térmica generada, etc. El objetivo de este trabajo es describir la técnica implementada y presentar su gran potencial de aplicabilidad, destacando su sencillez, fiabilidad y el bajo costo de la instrumentación utilizada.

----- *Palabras clave*: Gasificación de biomasa, monitoreo, diagnóstico, composición del gas pobre, control de procesos.

Introduction

Currently the 90% of the world primary energy consumption is fossil energy (oil, gas and coal). The growing trend to use fossil fuels is causing serious social and economical problems, and geopolitical instability and pollution. The main environmental problem is the global warming. The energy consumption in Colombia is also strongly dependent on fossil fuels (about 60%). According to the *Instituto de Planificación y Promoción de Soluciones Energéticas* (*IPSE*, acronym in Spanish) the areas in Colombia which are not interconnected to the electrical net (ZNI, acronym in Spanish) are about the 66% of the country area. This territory is inhabited by 1.831.822 people and the 95% of the energy is produced by fossil fuels.

One of the alternatives to produce electric energy by means of biomass is through its biomass gasification. The thermochemical process produces a gaseous fuel that can be used to fuel reciprocating internal combustion engines (RICE) or gas turbines. This technology can be used to produce energy in not interconnected areas, and the maximum electric power is about 500 kWe with RICE coupled to a downdraft biomass gasifier.

In this work a real time diagnosis method of the biomass gasification process in a downdraft reactor is presented. The method is based on the producer gas composition measured in a gasification pilot plant (40 kWt). The electric energy plants based on biomass gasification call for fullest attention to monitor the process and calculate its main parameters and decide when there are faults in the process. The diagnosis model can be an important module of the control system to optimize the plant performance.

Due to the simplicity and the low cost of the instrumentation needed to implement the method, it is underlining the potential of this tool. This can be classified as fault detection, thermochemical process evaluation and an important submodel of plant control system.

Combustion processes in real systems can be modeled by non-dimensional or dimensional models. The main objective of these mathematical approaches is to predict the gas composition and temperature at the outlet or through the whole length of the combustion device. This kind of models can be classified as predictive [1]. On the other hand, the combustion process can be also studied from exhaust gas analysis. If the reaction is ca-

rried out with an excess air, a complete combustion can be assumed and it is possible to calculate the fuel/air ratio measuring the O_2 concentration in the exhaust gas. In the case of incomplete combustion, additional data such as CO, NOx and unburned hydrocarbons concentrations are required to obtain accurate results. These studies can be classified as diagnosis models [2].

There is a wide variety of works that study the biomass gasification process evaluating the influence of the input parameters in the gas composition and the heating value of the producer gas [3 -7]. But a diagnosis model of the biomass gasification process, useful in fixed and fluidized bed gasifiers, is still missing in the literature.

Wander et al. [8] studied the gasification process in a small downdraft gasifier by means of several parameters experimentally obtained (gas composition, solid and gas flow, temperatures in the bed). Mass and energy balances for the gasifier were carried out and its cold gas, global and mass conversion efficiencies were determined as functions of air/fuel ratio. A similar investigation was executed by Zainal et al. [9] using a downdraft fixed bed gasifier. They investigated the effect of the air/fuel ratio on gas composition, calorific value and production rate. Other kind of analysis and mass, energy and exergy balances in an updraft fixed bed gasifier were presented by Rao et al. [10]. Majanne et al. [11] developed a diagnostic model for the fuel gasification process based on the flows, temperatures, pressures, and other measurements in the subprocesses monitored (fuel feed, gas cooling, gas cleaning, air compression and ash removal). The model can detect some faults and give information about the operation of the process.

By manipulating some equations used in predictive models it is possible to determine the input of such models (air-fuel ratio) from the measured outputs. This is the philosophy of a diagnostic model, being also possible to calculate some operation parameters such as gasifier efficiency and fuel consumption. The diagnostic approach is a powerful way to improve gasification systems and data evaluation. In addition, since the concentration of the more relevant gaseous species in the producer gas is high, it is not necessary an extreme precision of the analyzers and costs are widely affordable. Moreover the diagnostic method proposed in this work only required the composition and the flow of the producer gas, whereas similar models need more input parameters, increasing the instrumentation investment to develop the diagnosis methodology.

Experimental

Installation setup and measurement system

The experimental setup used in this work consists of a gasification system based on a gas producer mainly thought for wood biomass. The gasifier is an open top downdraft fixed bed reactor with an internal diameter of 190 mm and a height of 3 m (Figure 1). Producer gas passes through a filter to gas cleaning. The reactor and filter work in a blower-generated depression. After the blower, the gas passes through the flow rate measurement device and a sample of it goes to the gas analyzer system. The producer gas is intended to fuel an internal combustion engine, but in this test the gas is burned in a continuous burner.

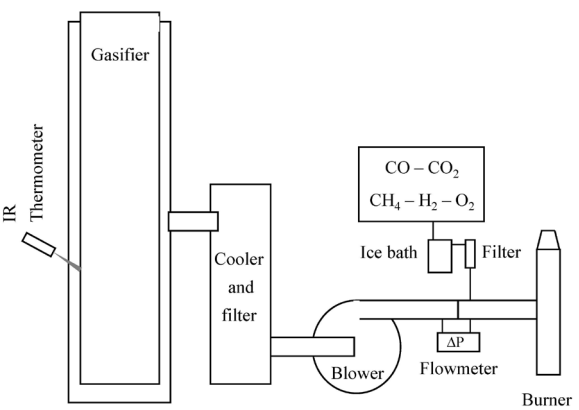

Figure 1 Experimental setup scheme

Gas temperature measurements were taken by thermocouples in different points. In particular at the reactor outlet, at the filter inlet and outlet,

near the flow rate measurement device and at the producer gas sampling spot. An optical pyrometer is used to measure the temperature at the reactor core.

Equipment for flow rate measurement is located at the tar filter outlet and consists of a pressure drop device and a differential pressure probe. The pressure drop is mathematically related to the flow rate according to a standardized procedure, Standard ISO 5167-1:1998 [12].

Pressure measurements are not considered to be relevant as the system is not pressurized. Thus the small pressure drops along the lines are neglected and in calculations pressure is assumed to be at its atmospheric value.

The producer gas analyzer system is composed by a tar filter and a preliminary gas cooling apparatus which makes water and tar residuals condensate, preventing the risk of damaging the instruments. The gas analyzer system is composed of infrared analyzers for CO, CO_2 and CH_4, a thermal conductivity analyzer for H_2 and an electrochemical analyzer for O_2.

As the gas specimen is supposed to be tar and water free there is no need for humidity and tar detection devices.

The measurement system described above constitutes all that is needed to carry out calculations. All data are collected by a PC acquisition board in order to be shown, stored and processed by a self-developed software application. It is very important to stress that all measurements of temperature, flow and gas chemical composition are continuously performed providing the chance to carry out a real time analysis of the process.

Data processing

From the biomass elemental analysis, water and ash free, it is possible to know the biomass fuel substitution formula CH_mO_p and the stoichiometric dry biomass-air ratio, see equations 1 to 3:

$$\mathrm{m} = \left(\mathrm{W_C Y_H}\right)/\left(\mathrm{W_H Y_C}\right) \quad (1)$$

$$\mathrm{p} = \left(\mathrm{W_C Y_O}\right)/\left(\mathrm{W_O Y_C}\right) \quad (2)$$

$$\mathrm{Fe} = \left(\mathrm{W_C} + m\mathrm{W_H} + p\mathrm{W_O}\right)/\left[\left(1 + m/4 - \mathrm{p}/2\right)\mathrm{W_{air}}\right] \quad (3)$$

The general chemical reaction process in the producer neglecting tars, carbon in the ash and minor compounds is expressed by the equation 4.

$$CH_mO_p + h \cdot H_2O + x \cdot (O_2 + 3.76N_2) \Rightarrow aCO + bCO_2 + cH_2 + dCH_4 + eH_2O + fN_2 + gO_2 \quad (4)$$

If there is some biomass in the ash, an error will be introduced in the biomass fuel substitution formula.

The equations for the atomic balances are presented in the equations 5 to 8:

Carbon balance:

$$1 = a + b + d \quad (5)$$

Hydrogen balance

$$m + 2h = 2c + 4d + 2e \quad (6)$$

Oxygen balance

$$p + h + 2x = a + 2b + e + 2g \quad (7)$$

Nitrogen balance

$$2(3.76)x = 2f \quad (8)$$

Five additional equations are obtained corresponding to the expressions of molar fractions for the gases that are measured experimentally, equations 9 to 13.

$$X_{CO} = a/\left(a + b + c + d + f + g\right) \quad (9)$$

$$X_{CO2} = b/\left(a + b + c + d + f + g\right) \quad (10)$$

$$X_{H2} = c/\left(a + b + c + d + f + g\right) \quad (11)$$

$$X_{CH4} = d/\left(a + b + c + d + f + g\right) \quad (12)$$

$$X_{O2} = g/\left(a + b + c + d + f + g\right) \quad (13)$$

As can be noted there are nine equations and nine unknown values ("*a*" through "*h*", plus "*x*").

Some auxiliary variables (equations 14 and 15) can be defined as follows:

$$\Sigma X_m = X_{CO} + X_{CO2} + X_{H2} + X_{CH4} + X_{O2} = 1 - X_{N2} \quad (14)$$

$$\Sigma X_{mc} = X_{CO} + X_{CO2} + X_{CH4} \quad (15)$$

From the ideal gas law and using the carbon balance, the eqution 16 to 18 are obtained.

$$(a+b+c+d+f+g)/(a+b+d) = (a+b+c+d+f+g) = (\Sigma X_m + X_{N2})/\Sigma X_{mc} = 1/\Sigma X_{mc} \quad (16)$$

$$f/(a+b+c+d+f+g) = (1-\Sigma X_m)/(\Sigma X_m + X_{N2}) = 1-\Sigma X_m \quad (17)$$

$$f = 1-\Sigma X_m/\Sigma X_{mc} \quad (18)$$

And from the nitrogen balance it turns out:

$$x = f/3.76 = (1-\Sigma X_m)/(3.76\,\Sigma X_{mc}) \quad (19)$$

And this way all the variables can be determined, equations 20 to 25.

$$a/(a+b+c+d+f+g) = X_{CO} \Rightarrow a = X_{CO}/\Sigma X_{mc} \quad (20)$$

$$b = X_{CO2}/\Sigma X_{mc} \quad (21)$$

$$c = X_{H2}/\Sigma X_{mc} \quad (22)$$

$$d = X_{CH4}/\Sigma X_{mc} \quad (23)$$

$$g = X_{O2}/\Sigma X_{mc} \quad (24)$$

The equivalence ratio is determined from the "x" value.

$$Fr = x_{st}/(x-g) = \Sigma X_{mc}(1+m/4-p/2)/[(1-\Sigma X_m)/3.76 - X_{O2}] \quad (25)$$

Finally, rearranging the oxygen and the hydrogen balances the parameter "(h-e)" can be obtained, see equation 26. It represents the amount of initial water that reacts. As can be noted it is impossible to calculate separately "h" and "e" as they are linearly dependent and do not appear in any other equation different from the oxygen and hydrogen balances.

$$h - e = c + 2d - m/2 \quad (26)$$

Taking into account the eight unknown variables and nine equations, it is then possible to use the last equation to calculate a checking parameter "m/2-p" that is compared with its experimental value, coming from the biomass chemical analysis, and thus to estimate the model reliability, equation 27:

$$m/2 - p = -a - 2b + c + 2d - 2g + 2x \quad (27)$$

Other possibility is to use only four analyzers and calculate the unknown measurement using the equation 28 derived from the expression of the checking parameter.

$$0.532 + 0.468\,X_{H2} + (1.468 + p - m/2)X_{CH4} = (1.532 - p + m/2)X_{CO} + (2.532 - p + m/2)X_{CO2} + 2.532\,X_{O2} \quad (28)$$

When the composition of the dry producer gas is known, it is possible to calculate the density of the gas passing through the flow meter in order to determine the producer gas mass flow. So the gas flow rate and the biomass rate can be known, see equation 29:

$$mfr_{bms} = mfr_{pg} \cdot F_{stq}F/(1+F_{stq}F) \quad (29)$$

As the flow rate of each gaseous component and its formation enthalpy are known, it is possible to calculate the producer gas high heating value, HHV. The biomass heating value can be experimentally measured by using a calorimetric bomb

[13]. Alternatively, the heating value can be estimated from the ultimate analysis of biomass, by using accepted procedures in literature [14].

The thermal efficiency of the gasifier can be defined as:

$$\eta = \left(HHV_{pg}\, mfr_{pg}\right) / \left(HHV_{bms}\, mfr_{bms}\right) \quad (30)$$

An approximate expression that can be used for operating purposes is:

$$\eta = \frac{\left[a\left(\Delta H^{o}_{fCO2} - \Delta H^{o}_{fCO}\right) + c\,\Delta H^{o}_{fH2O} + d\left(\Delta H^{o}_{fCO2} + 2\,\Delta H^{o}_{fH2O}\right)\right]}{\Delta H^{o}_{fCO2} + m/2\,\Delta H^{o}_{fH2O}} \quad (31)$$

Which requires data obtained from the gas composition analysis and the biomass composition (parameter "m"). Finally, the gasifier thermal power can be immediately calculated.

Sensitivity analysis

A sensitivity study of the diagnostic method has been carried out in order to analyze the influence of measurement errors on the final results. This study is summarized in Figure 2. The graphs show the value of the derivatives of some variables (e.g. Equivalence ratio) with respect to the value of each measurement. The derivatives are calculated at a point determined by a reference value of concentrations: CO=15%, H_2=13%, CH_4=4%, CO_2=9%, O_2=5%. This point was determined by the rounded average measurements. It can be observed for example that a 1% increment in the value of CO measured concentration has a negative effect on the efficiency, because that supposes water decomposition to decrease. It is important to take into account that this conclusion is valid in the case of an error in the measurement system, but it is not probably valid for a real increment of CO concentration as the H_2 concentration would also be augmented.

Water production has a similar influence but it has a different effect for each producer gas component depending on whether it contains or not hydrogen. The effect on the efficiency is similar but less important.

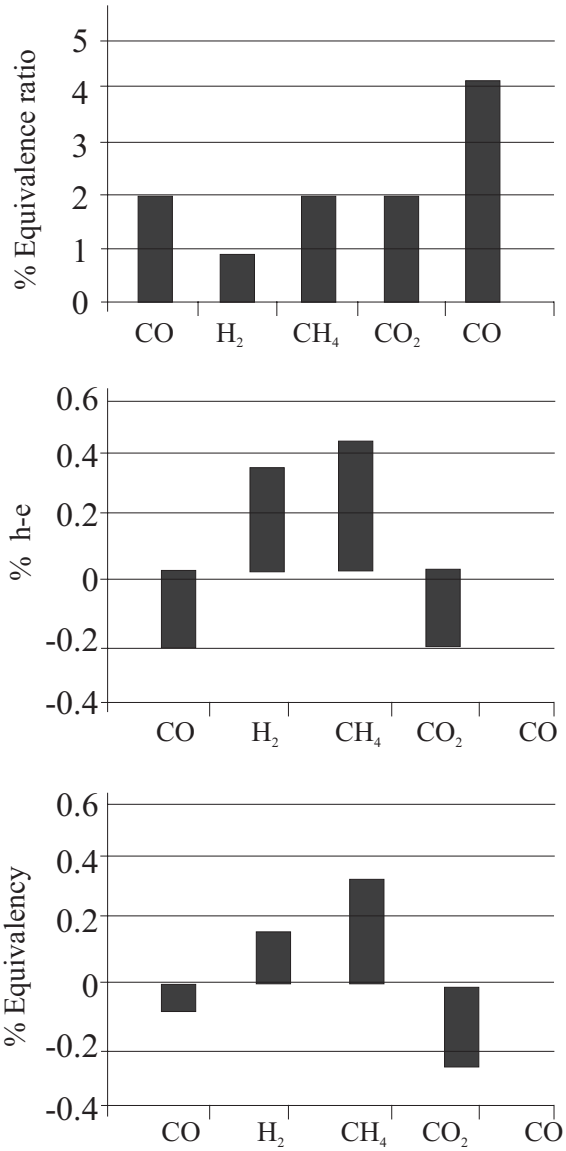

Figure 2 Absolute variation of equivalence ratio, variable h-e (moles) and efficiency due to a 1% variation of CO, H_2, CH_4, CO_2, O_2 concentrations

Figure 2 suggests that an error of 1% in the concentrations produces a remarkable error in the equivalence ratio of about 5%, with the major effect caused by the oxygen concentration.

In this analysis only the influence of an analyzer error was studied. The influence of an error in

the elemental analysis or the presence of biomass in the ash is determined directly from the equations. The parameter "m" has a notable influence on the water decomposition and on efficiency, while both parameters are independent from "p".

Results and discussion

A test was performed using pine pruning biomass, with an empirical formula $C_1H_{1.5}O_{0.51}$ and moisture of 18%. During the entire test the blower speed was kept constant. Figure 3 shows the analyzer records during all test time. CO and H_2 concentrations were constant except in the last part of the test, from 17000 s to 20000 s and from 25000 s until the test end. The bed reactor underwent a problem due to ash agglomeration; thereby the mass flow was decreasing during the second half of the test. The O_2 concentration remained stable around 5%. CO_2 and CH_4 concentrations were constant around 8% and 4% respectively except when CO and H_2 were decreasing.

The continuous fluctuations of records may be due to the non-uniformity of the biomass reacting at each moment. Figure 3b shows the same results of the 3a after they have been filtered using a low pass filter to clarify the exposition, without loss of key information for the understanding of the gasifier behavior.

During the first half time CO and H_2 concentrations showed no similar tendencies. During the second half time, when the agglomeration problem appeared, both concentrations decreased in the same way. CO_2 and CH_4 had a similar behavior though the fluctuations were proportionally more relevant for methane.

Once the general reaction coefficients are calculated, the concentration evolutions can be immediately obtained. They are iteratively corrected discounting the O_2 and the corresponding N_2 coming from air supposed to infiltrate from some unidentified spot along the pipelines, as shown in Figure 4a.

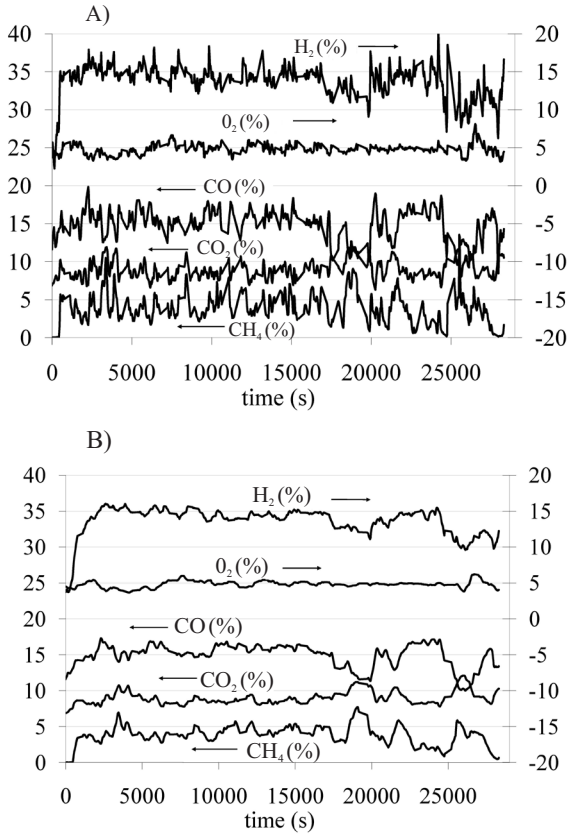

Figure 3 Analyzer records: unfiltered (a) and filtered (b)

Figure 4 shows the calculated parameters (thermal efficiency, relative equivalence ratio, checking parameters "*m/2-p*" and water decomposition) this parameters permit to deepen the analysis of the gasifier behaviour. In the time interval 0-10000 s, F_r was increasing up to about 4.25 but the efficiency remained constant around 0,7. A reason for the low efficiency can be found in the reactor size (190 mm in diameter) due to the lesser adiabatic characteristics. After 17000 s, thermal efficiency, water decomposition and Fr underwent a decreasing tendency and showed fluctuations due to an inadequate gasifier performance. This is confirmed in Figure 5 where the thermal power of gasifier, the biomass mass flow rate and the producer gas flow rate are shown. At the beginning, mass flow of producer gas reached 25 kg/h but it decreased quickly because of increments of pressure drop through the bed and because of the gasifier heating. Then the mass flow

decreased slowly, while the thermal power took a clear and strong decreasing tendency. Probably in this point the bed was too dense for the gasifier to work properly.

The biomass mass flow remained constant until 17000 s, and then it decreased as the producer gas mass flow rate did. The temperature evolution was similar to the producer gas mass flow rate.

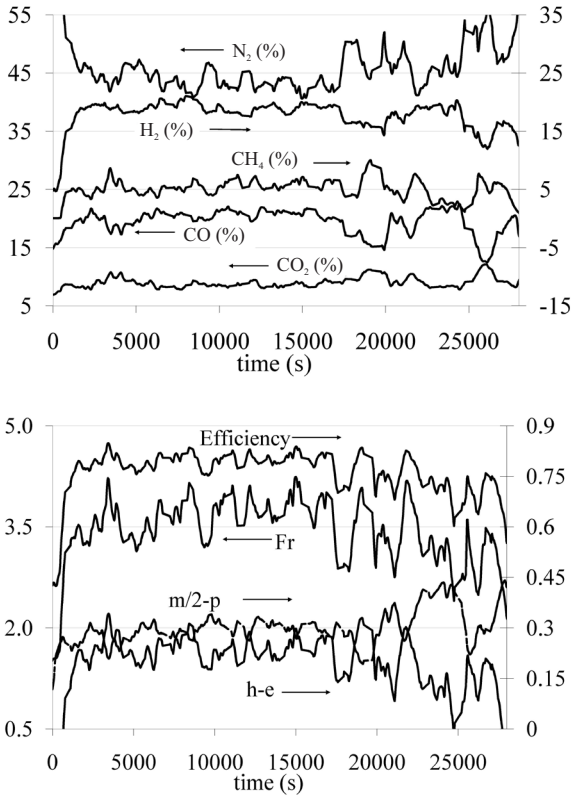

Figure 4 Corrected concentrations (a) and calculated variables (b)

The most interesting application of the procedure, apart from direct process analysis and check up, is the possibility of obtaining correlations among the various relevant parameters, which synthesizes the plant operation characteristics analyzed, such as gas composition analysis, equivalence ratio, efficiency, thermal power, and others. The development of optimum values can be the key to control and monitoring the biomass gasification plants. In Figure 6a it is possible to appreciate the effect that equivalence ratio has on efficiency and water decomposition. Tendencies were similar but the water decomposition showed a bigger dispersion. When the equivalence ratio was low water was produced (negative value of "h-e") and the efficiency dropped. Figure 6b shows the concentration trends of hydrogen, carbon monoxide and methane. Methane and hydrogen increased with equivalence ratio. The carbon monoxide seemed to be quite independent from the equivalence ratio. The hydrogen produced by water decomposition is used for methane and hydrogen production.

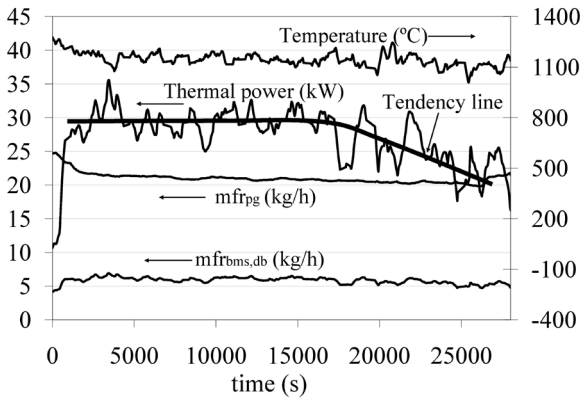

Figure 5 Evolution of temperature, thermal power of producer gas and mass flow rate of producer gas and biomass

Conclusions

This work shows that it is possible to perform a diagnostic of a gasifier by using only the gas composition analysis. The most important parameters can be obtained and monitored in real time. The system of equations coming from the atomic balance and the analyzers outcomes is incompatible and it is then necessary to establish new grouping variables: (h-e) representing water decomposition and (m/2-p) as a checking factor, looking for the solution of the equation system.

For a better understanding of the experimental results corresponding to gas composition it is convenient to filter them by a low pass filter. A producer malfunctioning can then be detected when, for instance, the thermal efficiency, equivalence ratio and thermal power decrease. These variables change as follows:

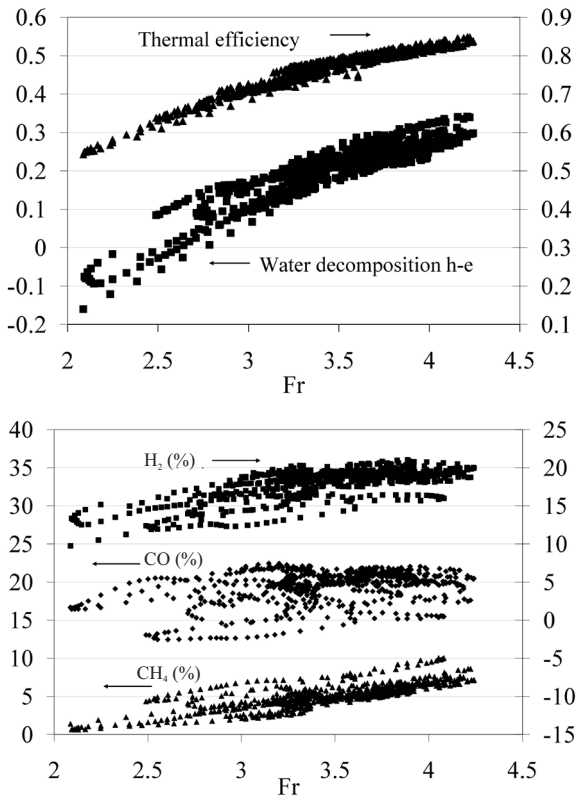

Figure 6 Efficiency and water decomposition versus equivalence ratio (a) and corrected concentrations versus equivalence ratio (b)

Thermal efficiency is strongly dependent on the equivalence ratio (proportional) and in the same way the thermal power. Water decomposition adopts different values even though thermal efficiency and equivalent ratio do not change. Finally, an equivalence ratio increase is accompanied by a higher methane concentration and a lower hydrogen concentration.

The methodology presented here can be easily extended in case of having more detailed information about the hydrocarbon composition in the producer gas, such as provided by a chromatographic technique. In that case, the assumed global chemical reaction (Eq. 4) can be modified to consider the stoichiometric coefficients for the new hydrocarbons whose concentration is experimentally measured.

The diagnosis model developed is a powerful tool, because it is possible to calculate in real time the most important biomass gasification parameters, such as equivalence ratio, efficiency, biomass consumption rate, thermal power, and others. Moreover, the model is useful for control, monitoring and fault detection in the biomass gasification plants.

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Nomenclature

a	Number of moles of CO produced (mol)
b	Number of moles of CO_2 produced (mol)
c	Number of moles of H_2 produced (mol)
d	Number of moles of CH_4 produced (mol)
e	Number of moles of H_2O produced (mol)
f	Number of moles of N_2 in products (mol)
g	Number of moles of O_2 in products (mol)
h	H_2O molar fraction in biomass (–)
F	Gasification process real equivalence ratio (–)
Fr	Equivalence ratio (–)
Fe	Stoichiometric dry biomass-air ratio (–)
HHV	Producer gas higher heating value (kJ/kg)
m	Atoms of carbon in the dry biomass (atoms)
mfr	Mass flow rate (kg/h)
p	Atoms of oxygen in dry biomass (atoms)
x	Reacting air moles (mol)
X	Molar fraction (–)
Y	Mass fraction (–)
W	Atomic weight (kg/kmol)
h	Thermal efficiency (–)
ΔHo	Standard enthalpy (kJ/kg)

Subscripts

Bms	biomass
pg	producer gas
air	air
O	oxygen
C	carbon
H	hydrogen atomic
N	nitrogen
O_2	oxygen gas
N_2	nitrogen gas
CH_4	methane
CO_2	carbon dioxide
CO	carbon monoxide
H_2O	liquid water
H_2	hydrogen molecular
m	measured
mc	measured containing carbon
st	stoichiometric

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