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Assessment of a small sawdust gasification unit

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Abstract

The use of sawmill residues must be carefully analyzed to offer the best technical, economic and environmental alternative. The characterization (quantity, type, chemical and energetic analysis) of the residues generated, in addition to the energetic needs of sawmills, is essential to determine which technology is more suitable. This study shows that the technology of wood gasification can produce a gas able to be burned in an internal combustion engine, as long as it is appropriately cleaned. In order to assess the performance of the wood residues gasification process, a small, fixed bed, downdraft, stratified and open top gasifier was built. This gasifier, whose capacity was around 12 kg/h, has an internal gas recirculation, new to this type of gasifier, which can burn part of the gas produced to raise the gasification reaction temperature. Through the several parameters measured in the experiments, the mass and energy balances of the gasifier studied were obtained and its cold gas, global and mass conversion efficiencies were determined.

Keywords: Wood residues; Gasification process; Downdraft gasifier; Gas recirculation; *Pinus elliottii*

1. Introduction

The saw mill sector of the Brazilian State of Rio Grande do Sul currently disposes off some of its residues (sawdust, bark and planer shavings) through environmentally incorrect means, with only a small amount going to be used as litter in the poultry industry. The surplus residue amount generated in Canela is 15,000 t year^{-1}, sufficient with current biomass to electricity technology to constantly generate 1.8 MW (assuming 7000 h year^{-1} capacity factor) [1]. In the United States [2] there are over 7 GW of installed capacity, generating about 45 TWh of electricity per year, and the average efficiency of power generation from biomass is between 20% and 25%.

An evaluation of the literature and the economic criteria that would meet the low electricity costs of Brazil suggests that systems generating electricity

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Nomenclature

ΔH^{o}	standard combustion heat, kJ kmol^{-1}
HHV	high heating value, kJ kg^{-1}
LHV	Low Heating Value, kJ kg^{-1}
m	mass flow, kg s^{-1}
M	molecular mass, kg kmol^{-1}
P	pressure, Pa
Q	heat flux, kW
Δ	difference
η	efficiency
ρ	density, kg m^{-3}
χ	molar fraction

Subscripts

N	normal conditions
i	ith component

at reasonable efficiency ($>25\%$) and with low investment costs of less than 600 \$ kW^{-1} can be viable solutions. In a survey completed by the authors [3], only gasification to produce a low calorific value gas to fire a diesel pilot ignition internal combustion engine can meet these criteria. From this we chose to work on the co-current moving bed gasifiers that are described in the literature as downdraft—stratified open top gasifiers.

Giltrap et al. [4] describes thermochemical gasification as a process for converting solid fuels into gaseous form. The chemical energy of the solid fuel is converted into both the thermal and chemical energy of the gas depending on its chemical composition. Downdraft gasification is a comparatively cheap method of gasification that can produce a product gas with very low tar content.

In the region nearest the air inlet, flaming pyrolysis processes occur. Highly exothermic combustion reactions provide the energy to pyrolyse (devolatilize) the solid fuel, and these two processes can occur nearly simultaneously. Beneath the flaming pyrolysis zone is the reduction zone where CO_2 and H_2O are reduced with carbon by endothermic reactions on the char surface. Some advantages of the biomass are: low cost by-product in agriculture and forestry; low ash and sulfur contents; and no CO_2 level increase in the atmosphere, since the biomass consumed does not exceed the forest production.

Chowdury et al. [5] present the modeling and simulation of a downdraft stratified gasifier for rice husk through a realistic model not based on the thermodynamic equilibrium, and compares its theoretical results with those of the experimental tests. Mukunda et al. [6] studied a downdraft stratified open top gasifier coupled to a Diesel engine. The total efficiency of the system measured in relation to the final electric energy was 27% in a 100 kWe unit. The cost of the electricity produced was 380.00 \$ kW^{-1}, i.e., approximately 50–60 \$ MW h^{-1}.tlsb

Walawender et al. [7] studied a model of gasifier (stratified and open top) commercially available called "Buck Rogers Gasafire®", projected to supply 90–440 kWt, where the main purposes of the study were to determine mass balance and quantitative efficiency of this type of gasifier. Nineteen tests were carried out, and nine of them obtained a closure larger than 95% and the worst result was 80%. The average composition of the gas produced on a dry basis is the following: $H_2 = 15.1\%$; $CO = 19.1\%$; $CH_4 = 2.5\%$; $CO_2 = 15.8\%$; small quantities of C_2H_6, C_2H_4 and C_3H_8 and the remainder is N_2.

Other interesting works were developed by a team of researchers of the Zaragoza University/Spain [8,9]. This team built two stratified-closed top gasifiers, one for 50 kg h^{-1} and another for 200 kg h^{-1} of the same configuration. The average composition of the gas produced on dry basis is in the following range of volume percentage: $N_2 = 45$–60%; $CH_4 = 0.25$–2.5%; $H_2 = 10$–22%; $CO = 13$–25%; $CO_2 = 8$–19% and traces of C_2H_2 and C_2H_4. The higher heating value of the gas varied between 4.2 and 5.4 MJ Nm^{-3}.

2. Gasifier details

The gasifier built has capacity to process approximately 12 kg h^{-1} of sawdust and is composed by a cylindrical body with 270 mm of internal diameter and 1100 mm height with a cast iron grate fixed to a rotating shaft (3–6 min per revolution) in the bottom. The gasifier body is made of SAE 1020 steel. Above the grate, on the shaft, rods are used to mix the sawdust in the reduction zone and to favor the extraction of the ash above the grate. In the center of the gasifier, a device like a venturi aspirates part of the gases produced inside it to be burned in a chamber. A scheme of the gasifier studied is shown in Fig. 1.

As it can be seen in Fig. 1, the equipment is also composed by an external concentric cylinder to exchange the heat of the leaving gas with the entering sawdust. Part of the internal diameter (up to 500 mm over the grate) is insulated with 30 mm of refractory cement. Below the grate there is an ash box. The entire external cylinder is insulated from the ambient with 50 mm of rock wool to minimize heat loss.

The sawdust feeding is manual and semi-continuous, introducing fixed quantities. The secondary air is injected into the inner burner through a centrifugal fan that supplies the pressure needed to carry out the internal gas suction.

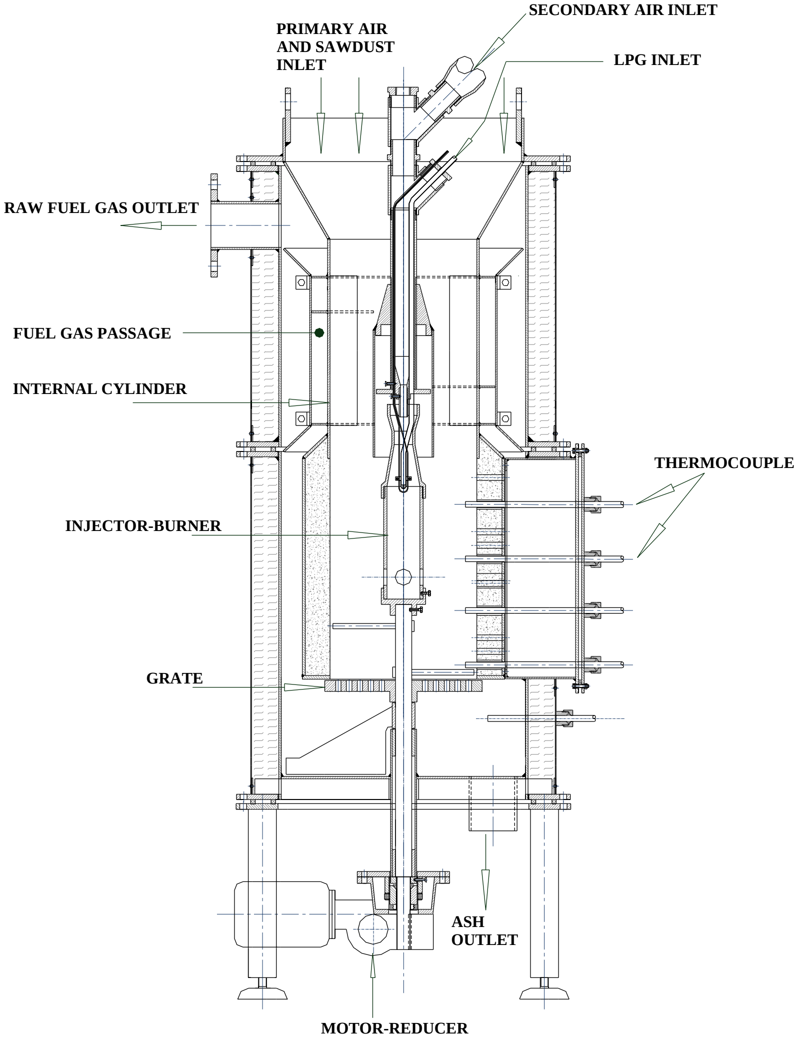

Fig. 1. Schematic drawing of the gasifier.

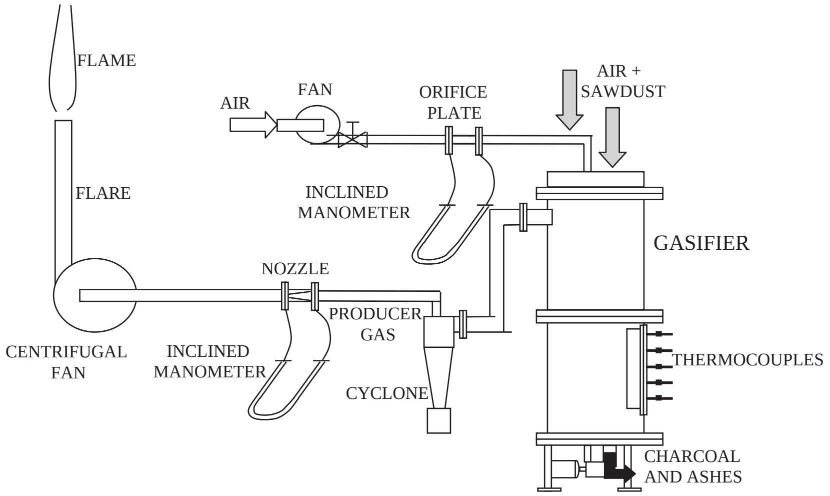

Fig. 2. Schematic of gasifier and instruments.

Another centrifugal fan aspirates the remainder air (primary air) and the fuel gas produced through all systems. The fuel gas is then burned in a flare. Fig. 2 is a diagram of the complete system.

The general literature shows that an equivalence ratio of $0.3 - 0.35\,\mathrm{kg_{O_2}\,kg_{wood}^{-1}}$ is required in successful gasification. In small gasifiers with high heat losses a greater value is required typically resulting in $2\text{–}2.4\,\mathrm{kg_{air}\,kg_{wood}^{-1}}$, producing a gas with a low calorific value of $4.0\text{–}6.0\,\mathrm{MJ\,Nm^{-3}}$.

As described before, pyrolysis produces gases and vapors that increase the total volume of gases. According to [10], the generic composition of the pyrolysis products could be $CH_{3.41}O_{1.58}$ with a LHV of $11.8\,\mathrm{MJ\,kg^{-1}}$ (determined with the mass fractions of its components). The heat generated with the burning of these products will increase gases energy and temperature favoring the reactions with the remaining charcoal.

3. Experiments methodology

The biomass used on the tests was *Pinus elliottii* sawdust. This exotic specie is widely cultivated in the south of Brazil. The bulk density, proximate and ultimate analyses of the sawdust were determined. The proximate analysis (moisture, volatile matter, char and ash) was determined using ASTM Standards. Three proximate analyses were made: one by the authors group and other two by CIENTEC/Porto Alegre. Two ultimate analyses were carried out by CIENTEC along with a calorific value test in a calorimeter. From the elemental specie percentages it is also possible to calculate the high and low heating values (HHV and LHV) of the sawdust, and compare with experimental data.

The mass balance is possible if both material and fluid (sawdust, air, fuel gas, charcoal and ash) flows are measured. Due to the characteristics of each measurement, the products were divided in solids and gases. The mass solids were determined by weighing the materials on an electronic scale. In the case of the sawdust, an estimated quantity to be used was previously weighed and after the test the sawdust that had not been used was weighed again. Dividing the mass difference by the test duration gives the biomass flow. Charcoal and ash were measured after the test too.

The tests were conducted under suction from a centrifugal fan powered by a frequency inverter device to change fan speed in such a way that the gas flow was kept approximately constant. The grate movement was also controlled with a frequency inverter to keep the sawdust flow through it.

Air and fuel gas flow measurements were determined using orifice plate and nozzle, respectively. In accordance to Fig. 1, the air flow is divided in two parts: secondary air, which is injected by a fan into the internal burner, and primary air aspirated by the open top of the gasifier, which is very difficult to measure directly. Only the secondary air was measured through the orifice plate, and the primary air was obtained indirectly by the mass balance.

The main uncertainty factor of measuring with these devices is the discharge coefficient, which depends on the Reynolds number. The pressure drop and temperature (upstream of the orifice plate and downstream of the nozzle) measurements were made at every 10 min.

After the gasification process has been established, gas samples were collected every 20 min, which were analyzed by gaseous chromatography on a CG-35 equipment. A dual column (Porapaq Q and MS5A) unit with thermal conductivity detectors and carrier gases H_2 and N_2 were used to measure the permanent gases collected in glass balloons containing non-reactant solution.

In some tests the tar content and the humidity was measured aspirating a gas sample through three glass water condensers, an 8-m glass coil placed inside an ice bath, a balloon with activated coal, a flowmeter, pump, and, at the end, through a molecular sieve to check the gas humidity. The material collected was evaluated using an appropriate chemical method to determine the tar and humidity quantities.

Through the temperature measurement it is possible to estimate the region where the pyrolysis, combustion and reduction reactions are occurring. Ten K-type thermocouples (Chromel–Alumel) were disposed in the reaction zone and installed from 25 mm above the grate up to the middle of the internal cylinder. The thermocouples were equally distributed with a 50-mm distance among each other (see at the right of Fig. 1).

The mass and energy balances were determined measuring the sawdust quantity, the gas flow, solid wastes (charcoal and ash), LPG quantity and secondary air. The total dry air is determined to close the mass balance and the sawdust and air moisture determines the water quantity. The mass balance equation is:

$$m_{\mathrm{air}} = m_{\mathrm{gas}} + m_{\mathrm{solids}} - (m_{\mathrm{sawdust}} + m_{\mathrm{LPG}} + m_{\mathrm{water}}). \tag{1}$$

The gas composition is an average of the samples analyzed during the tests. With it is possible to calculate the gas high heating value (HHV) from the combustion heat of the gas components

$$\mathrm{HHV} = \rho_{\mathrm{N}} * \sum\nolimits_1^n [\chi_i(-\Delta H_i^{\circ})] * 0.001 * M^{-1}, \tag{2}$$

where ρ_{N} is the specific mass (kg Nm^{-3}) at normal conditions ($p = 101.325$ kPa and $t = 25\,^{\circ}$C) and considering the ideal gas behavior; χ_i is the molar fraction of the ith component, ΔH_i° is the standard combustion heat (J mol^{-1}); n is the number of components in the gas sample; M is the molecular mass (kg kmol^{-1}) and 0.001 is a conversion factor.

The main difficulty found on the uncertainty assessment was due to the great quantity of variables measured and to the different operational conditions determined by the characteristics of the equipment. The main uncertainty is related to the gas flow measurement and its composition.

The solid masses were measured in an electronic balance with an uncertainty of $\pm 0.3\%$. The uncertainty of the gas flow measurement was considered as $\pm 6.9\%$. A full propagation of errors analysis led to an error of approximately $\pm 7.2\%$ in the cold gas and global efficiencies, and $\pm 0.3\%$ in the mass conversion efficiency.

4. Results and discussions

As commented before, three proximate and two ultimate analyses were made in the biomass used in the tests (*Pinus Elliottii* sawdust). The results are reported in Tables 1 and 2.

Before each test, the moisture content of the sawdust was measured and its value was always between 9% and 11%. Its granulometry was a mixture of powder with a diameter ranging from 1 to 2 mm and plane shavings with characteristic length from 5 to 20 mm. During the tests, the sawdust level inside the gasifier was maintained approximately constant in a certain height, and the

Table 1
Sawdust proximate analyses (wt %)

Component	UCS		CIENTEC 1		CIENTEC 2	
	db	wb	db	wb	db	wb
Moisture	—	10.66	—	10.63	—	12.93
Volatile matter	82.54	73.74	86.40	77.22	86.48	75.30
Fixed carbon	17.13	15.30	13.50	12.06	12.93	11.26
Ashes	0.34	0.30	0.10	0.09	0.59	0.51
HHV (kJ g^{-1})	21.001		20.407		20.100	

Table 2
Sawdust ultimate analyses (wt %)

Element	Sept 1999	Aug 2001
Carbon—c	52.00	50.91
Oxygen—o (by diff)	41.55	42.14
Nitrogen—n	0.28	0.23
Hydrogen—h	6.07	6.13
Sulfur—s	—	—
Ash—as	0.10	0.59
HHV (MJ kg^{-1})	20.407	20.100
LHV (MJ kg^{-1})	19.074	18.877

level variation was up to 50 mm between each feeding.

After the gasification process a little quantity of carbon is not converted in fuel gas and remains charcoal and ash. All solid waste was considered as charcoal. The charcoal grain sizes ranged from very small values (powder) up to 5 mm.

The results of 12 tests are presented in Table 3. These results lead to the mass and energy balance of the gasifier studied.

According to the methodology section, the gas samples were analyzed and the average of the compositions are shown in Table 4. The sample gas was collected after the cyclone.

With the compositions reported in Table 4, it is possible to calculate the cold gas efficiency by using the following equation:

$$\eta_{\text{cold gas}} = 0.92 * m_{\text{gas}} * \text{HHV}_{\text{gas}} * [\rho_N (m_{\text{sawdust}} \text{HHV}_{\text{sawdust}} + m_{\text{LPG}} \text{HHV}_{\text{LPG}})]^{-1}, \quad (3)$$

where 0.92 is a factor to consider the presence of tar and condensables in the gas flow measured; m_{gas} is the fuel gas mass produced reported in Table 3; HHV_{gas} is the high heating value of the fuel gas (Table 4); m_{sawdust} is the dry sawdust used in the test (Table 3); $\text{HHV}_{\text{sawdust}}$ is the high heating value of the sawdust, which was considered equal to 20.10 MJ kg^{-1} (Table 2); m_{LPG} is the LPG mass used in the test (Table 3) and HHV_{LPG} is the high heating value of the LPG, which was considered equal to 49.186 MJ kg^{-1}. The results of efficiencies and other ones are shown in Table 5. The carbon closure presented in Table 5 was calculated dividing the carbon percentage in the gas and the char by its percentage in the biomass (considering the carbon percentage of the char as 80%).

The global efficiency considers the charcoal as a byproduct of the installation, and hence, the term $m_{\text{char}}\text{HHV}_{\text{char}}$ was considered in the numerator of the Eq. (3), where m_{char} is the charcoal mass reported in Table 3, and HHV_{char} is its higher heating value (considered as 29.7 MJ kg^{-1}). The carbon closure achieved an average of 92.51% with a standard deviation of 12.50%.

The equipment was constantly adjusted and improved. The first five tests were performed without gas recirculation. In some tests, the flame changed from reddish and lengthy to a somewhat orange and short. A characteristic temperature profile obtained in the test GSR4 without gas recirculation is shown in Fig. 3.

The profile showed that very high temperatures were not reached. This was an unstable test, and the consequence was a significant variation of the gas composition from one sample to the other. A

Table 3
Mass balance of the tests

Test	Sawdust	Inlet ($kg\,h^{-1}$)			H_2O[b]	Oulet ($kg\,h^{-1}$)		Air/Saw[d]	Sol/Saw[d] (%)
		LPG	Sec. air.	Prim. air[a]		Wet gas	Char[c]		
GSR1	8.13	0.6	11.27	12.15	1.45	33.36	0.23	2.88	2.84
GSR2	16.37	—	11.05	4.06	2.60	31.68	2.41	0.92	14.71
GSR3	15.07	0.326	8.16	18.84	2.33	44.34	0.39	1.79	2.60
GSR4	10.96	—	9.85	15.87	1.74	37.77	0.66	2.35	6.04
GSR5	15.12	0.209	7.00	7.15	2.01	30.49	1.00	0.94	6.62
GCR1	10.23	0.114	2.51	14.51	1.31	27.73	0.95	1.66	9.31
GCR2	9.73	—	7.04	7.24	1.56	25.38	0.21	1.49	2.13
GCR3	8.15	—	7.62	15.04	1.35	31.53	0.63	2.80	7.68
GCR4	8.67	—	8.02	8.74	1.38	26.23	0.58	1.87	6.68
GCR5	12.50	—	9.54	6.45	1.55	28.96	1.08	1.28	8.61
GCR6	13.98	—	7.30	8.16	1.72	30.32	0.84	1.11	6.00
GCR7	11.50	—	7.86	14.37	1.64	34.96	0.43	1.93	3.71

[a] Indirectly calculated to close the mass balance.
[b] Sawdust moisture + air moisture.
[c] Total quantity of solids (ash + sawdust not converted).
[d] At dry basis.

Table 4
Fuel gas composition (vol %)

Test	CO	H_2	CH_4	N_2	CO_2	C_2H_4	C_2H_6	Total
GSR1 (3 samples)	16.00	10.93	2.58	56.71	13.22	0.50	0.06	100.0
GSR2 (2 samples)	18.69	10.63	3.41	52.25	14.10	0.76	0.16	100.0
GSR3 (3 samples)	22.71	13.01	2.91	45.91	14.57	0.79	0.10	100.0
GSR4 (3 samples)	20.84	10.27	1.08	55.98	11.43	0.26	0.14	100.0
GSR5 (2 samples)	20.32	15.64	3.65	47.61	11.81	0.80	0.17	100.0
GCR1 (3 samples)	20.95	14.38	2.38	51.63	9.73	0.67	0.26	100.0
GCR2 (3 samples)	20.20	17.38	2.18	46.85	12.79	0.51	0.09	100.0
GCR3 (3 samples)	15.77	10.27	2.05	60.92	10.29	0.59	0.11	100.0
GCR4 (3 samples)	19.54	13.13	2.40	52.23	11.98	0.59	0.13	100.0
GCR5 (0 samples)	—	—	—	—	—	—	—	—
GCR6 (1 sample)	19.48	18.89	3.96	44.95	12.01	0.61	0.10	100.0
GCR7 (3 samples)	17.23	10.93	1.28	57.97	11.94	0.53	0.12	100.0

typical temperature profile obtained in the tests with gas recirculation also is shown in Fig. 3. The temperatures reached in these tests were higher than former tests, and its profile assumed characteristics expected for the internal regions of the gasifier and its respective reactions.

On GCR6, for example, the temperature at the gases internal burner outlet level and beneath was around 900 °C. After that, there is a decrease to 800 °C just above the grate, indicating first some combustion and then reduction of the gases with charcoal. The records of temperature profile show a steady behavior in this region. The recirculation occurred during all test time.

On GCR6 test, the flame produced was always stable with a medium length, changing from

Table 5
Heating values and efficiencies

Test	Mol. Mass (kg kmol^{-1})	Density (kg Nm^{-3})	HHV (MJ Nm^{-3})	Gas prod. (Nm^3 bs^{-1})[a]	η_{conv}[b] (%)	$\eta_{cold\ gas}$ (%)	η_{global} (%)	C closure (%)
GSR1	26.9790	1.1028	4.3938	3.42	97.16	63.41	66.96	113.18
GSR2	27.1005	1.1078	5.1858	1.61	85.29	41.46	63.19	82.06
GSR3	26.6151	1.0879	5.7253	2.49	97.40	67.31	70.96	104.77
GSR4	27.0452	1.1055	4.2430	2.87	93.96	60.51	69.44	103.89
GSR5	25.4031	1.0384	6.0766	1.79	93.38	52.24	61.71	75.39
GCR1	25.5546	1.0446	5.5281	2.39	90.69	63.89	77.29	95.03
GCR2	25.2817	1.0334	5.5125	2.32	97.87	63.65	66.79	84.74
GCR3	26.7466	1.0933	4.1786	3.26	92.32	67.67	79.02	104.68
GCR4	26.2322	1.0723	5.0940	2.60	93.32	65.82	75.69	99.07
GCR5	—	—	—	2.09	91.39	—	—	87.13
GCR6	24.5515	1.0036	6.3206	1.99	94.00	62.50	71.36	77.44
GCR7	26.9300	1.1009	4.1177	2.54	96.29	52.03	57.52	82.74

[a] Dry sawdust.
[b] Only solid losses (100 − sol./sawdust).

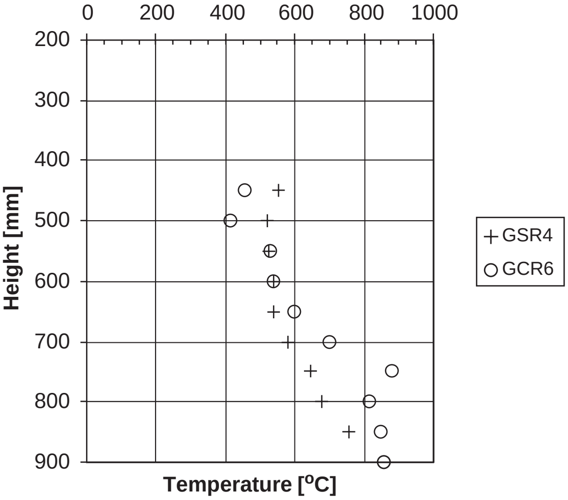

Fig. 3. Temperature profile on tests with and without gas recirculation.

yellow, at the beginning, to orange along the test, without any particulate. During almost all test time the flame was sustained, i.e., without pilot flame. The value of the air/sawdust ratio was very low, 1.11 (equivalence ratio of 0.26), and the mass conversion was relatively low, i.e., approximately 94%. The moisture content and tar measured were respectively 11.61% and 2207 ppm. In the tests without recirculation and part of the tests with recirculation, tar contents were not measured. An average of three tests showed a humidity of 9.75% and a tar content of 2136 ppm.

In Fig. 4 the efficiencies of the gasifier versus the air/sawdust ratio are shown. The air/sawdust ratio must be maintained above 1.5 (equivalence ratio of 0.35) to guarantee the expected reactions with cold gas efficiency over 60% in the gasifier without recirculation.

In Fig. 4 is showed that mass conversion is relatively independent of the air/dry biomass ratio, while the global efficiency depends on both mass conversion and cold gas efficiency. It seems that in the tests with recirculation (Fig. 4b) good efficiencies were obtained at relatively lower air/dry biomass ratios (1.1–1.4). This may happen due to the lower need of air to burn the recirculated gases, instead of the charcoal, and the consequent high temperatures obtained, which favor the reduction reactions.

In Fig. 5, an average of the three higher temperatures inside the gasifier was plotted versus mass conversion, global and cold gas efficiency for the tests (a) without and (b) with gas recirculation. It can be seen that higher temperatures were obtained in the tests with gas recirculation (at the test with temperature below 800 °C, recirculation did not work properly).

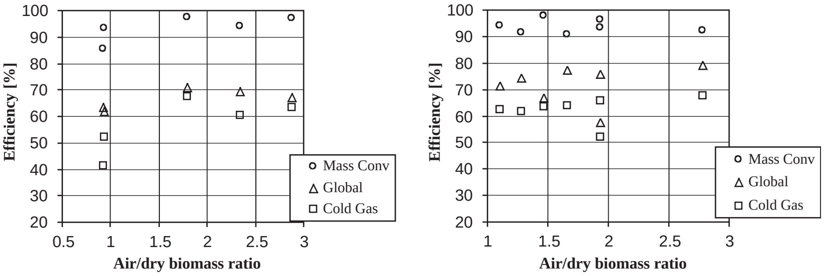

Fig. 4. Gasification efficiencies versus air/dry biomass ratio (a) without and (b) with gas recirculation.

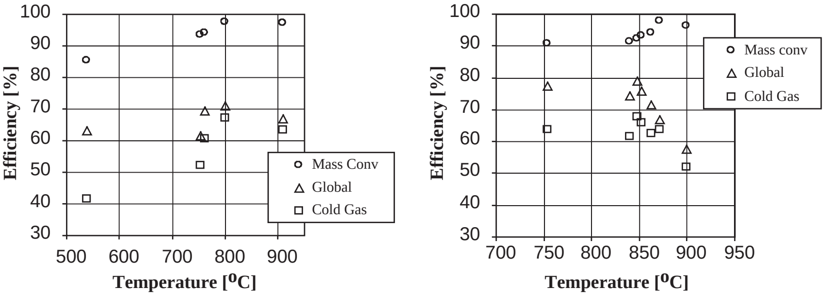

Fig. 5. Gasification efficiencies versus temperature (a) without and (b) with gas recirculation.

Those tests with values of mass conversion below 95% and temperature above 800 °C in Fig. 5b were started with charcoal (~12% of the wood used) to heat up the internal parts. Probably an amount of unreacted carbon passed through the grate increasing the mass of solids at the end of the test. Mass conversion efficiency decreases for temperatures below 800 °C and is clear that when there is a high conversion, the difference between cold gas and global efficiencies (which takes in account the possibility of charcoal usage) decreases.

Other important issues were observed like the need of a strong mixing of the sawdust due to its characteristic of bridging and channeling. The small size of the biomass particles allows the easier passage of them through the grate. Also manufacturing aspects must be observed due to the high temperatures obtained in the combustion chamber. The way chosen to take out ash and char, through a water seal, is inadequate because char–ash is lighter than water and will float on it blocking the passage.

5. Conclusions

The figures show that gas recirculation improved the efficiencies of the equipment and higher internal temperatures were achieved. Although tar reduction was not measured, there were good indications of it. The temperature measurement was useful to understand the internal reactions and the flame aspect and color gave good indications on how the gasification proceeded. Bridging and channeling, grate control and high wear of internal parts were the main operational problems encountered.

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