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COMPARISON OF THE GASIFICATION POTENTIAL OF RICE HUSK SAMPLES FROM BRAZIL AND THAILAND

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RESUMO – This work aimed at comparing the gasification potential of rice husk samples from Brazil (CAZ1) and Thailand (CAZ2). The pyrolysis step was performed in two pyrolysis reactors under different conditions. The product yields were determined and related to the pyrolysis conditions applied. The biomass and rice husk chars were characterized and overall char combustion and gasification reactivities were measured by thermogravimetry in synthetic air and in CO_2, respectively. The differences in samples properties play important roles in the thermochemical conversion steps. These differences may reflect local variations of the agricultural growing conditions, as noticed between the two rice husk samples studied, being the Thai rice husk char more reactive than the Brazilian one both in air and CO_2 gasification.

1. INTRODUÇÃO

Rice husk is an important agroindustrial solid residue both in Brazil and Thailand. Many studies in the literature dealt with the relation between pyrolytic conditions with either char reactivity or char structure during biomass gasification (Pindoria *et al*, 1998; Mansaray and Ghaly, 1999; Mansaray *et al*, 1999; Adánez *et al*, 2001; Biagini *et al*, 2008; Asadullah *et al*, 2009). The parameters studied include heating rate, final temperature, pressure, residence time of volatiles and particle size and distribution (Guerrero *et al*., 2005; Cousins *et al*, 2006 a, b; Biagini *et al*., 2008). The char structure affects the subsequent oxidation step given that the pores size and distribution determines the accessibility of the reaction gas to the active sites (Bar-Ziv *et al*, 1998; Arenillas *et al*, 2002). Compared with most bituminous coals, biomass materials present significant amounts of alkali and alkaline earth metallic (AAEM) species (mainly K, Na, Mg and Ca), which tend to volatilise during pyrolysis (and gasification/combustion), being of important consideration in all aspects of biomass thermochemical conversion. When retained in char during pyrolysis, are important catalysts for the gasification/combustion of char (Raveendran and Ganesh, 1998; Zolin *et al*, 2001), helping to reduce the gasification temperature and increase the overall process efficiency.

2. MATERIAL AND METHODS

2.1. Biomass characterisation

The Brazilian rice husk sample (CAZ1) was characterised as described below. The characterisation results for the rice husk sample from Thailand (CAZ2) have been provided by the researcher Yatika Somrang and only the results have been reported. CAZ1 and CAZ2 samples were ground and sieved to (106-150) µm sized particles and dried in a re-circulating air oven at 35 °C for 16 h, stored in small glass bottles in the fridge at approximately 6 °C prior to pyrolysis experiments.

2.1.1 Proximate and ultimate analyses: Proximate analysis (moisture (M), volatile matter (VM), ash (A), fixed carbono (FC)) was carried out following DIN 51718 (DIN, 2002), DIN 51720 (DIN, 2001) and DIN 51719 (DIN, 1997), respectively. Ultimate analysis (C, H, N, S, O) was carried out according to the ASTM D3176 method (ASTM, 1997). The oxygen content was calculated by difference. Chloride was measured using selective ion electrodes (Cole-Parmer).

2.1.2 Heating Value: The Higher Heating Value (HHV) and the Lower Heating Value (LHV) were determined by applying the methods ASTM D5865 (ASTM, 2004) and DIN 51900 parts 1 and 3 (DIN, 2000; DIN, 2005) to samples previously dried. The HHV was determined in a calorimeter and the LHV was calculated using the Dulong equation (1), with HHV and LHV in MJ.kg^{-1}, H is the mass fraction of hydrogen and M the moisture content of the sample:

$$LHV = HHV - 2.43 \cdot (9 \cdot H + M) \tag{1}$$

2.2. Biomass pyrolysis

Pyrolysis experiments were carried out in: (1) a horizontal tube furnace (TF) and (2) a hot-rod reactor (HRR), which were described by Virmond (2011). The operating conditions were presented in Table 1. The residence time was previously tested and 900 s was the minimun necessary to promote complete devolatilisation of the sample at the temperatures evaluated.

Table 1 – Conditions applied to the pyrolysis experiments with CAZ1 and CAZ2

	PS[a] [µm]	T[b] [°C]	HR[c] [°C.s^{-1}]	t$_r$[d] [s]	Gas[e]	p[f] [bar]	v$_s$[g] [m.s^{-1}]
Tube furnace							
CAZ1	(106-150)	350, 500, 700, 850	0.8	900	N$_2$	1.0	0.1
CAZ2	(106-150)	350, 500, 700, 850	0.8	900	N$_2$	1.0	0.1
Hot-rod reactor							
CAZ1	(106-150)	500	1	900	He	2.2	0.1
CAZ2	(106-150)	500	1	900	He	2.2	0.1

[a] Particle size; [b] Pyrolysis temperature; [c] Heating rate; [d] Residence time at the pyrolysis temperature; [e] Carrier gas; [f] Pressure inside the reactor; [g] Superficial velocity of the carrier gas.

2.1.1 Pyrolysis in the TF: A tube furnace (STF Model 16/180, Carbolite) was used. A quartz tube of 10 mm internal diameter, 12 mm outer diameter and 113 cm long was fitted into the ceramic tube of the furnace to serve as a support for the sample holder assembly and to limit the pyrolysis environment for smaller mass samples. Sample mass between 0.085 and 0.200 mg of pre-dried biomass were reacted. Each test was repeated at least twice (the repeatability was tested for one sample/condition in five runs at the same conditions). The spread of the data has been estimated by calculating the standard deviations from the results of multiple tests.

2.1.2 Pyrolysis in the HRR: The description of the version of the reactor developed by the

Combustion, Gasification and CO_2 Capture group from the Imperial College London and used in the present study as well as of the reactor operation was given by Dabai *et al.* (2010). The HRR runs have been performed with only the first of two stages, which was connected directly to the tar trap. A flow of inert gas (He) was used to sweep the released volatiles into the tar trap placed in a liquid nitrogen bath so that the volatiles released from the reactor could be condensed and trapped. Each test was repeated 1-2 times. The spread of the data has been estimated by calculating the standard deviations from the results of multiple tests. Gas chromatography device (model Clarus 500, Perkin Elmer, FID/TCD) has been used to characterise and quantify the gas components condensed in the tar trap. A packed Alumina F-1 60/80 column was used for analysis of hydrocarbons and a packed Hayesep N60/80 mesh column for CO_2 determinations. CH_4 and CO could not be efficiently collected in the tar trap. Two online ADC analysers based on infrared detection were used to measure the amount (%) of these gas components. The analysers were previously calibrated with a certified gas mixture (supplied by BOC gases).

2.3. Characterisation of the pyrolysis char

2.3.1 Proximate and elemental composition: The ultimate analysis (CHN) of CAZ1 and CAZ2 char samples produced in the TF at 500 °C and 850 °C, and in the HRR at 500 °C was carried out according to the ASTM D3176 method (ASTM, 1997). The oxygen content was calculated by difference. The contents of moisture, volatiles and fixed carbon were obtained from the TGA experiments performed for measuring the combustion reactivity in a instrument TGA Q 500 (TA Instruments Inc.), such as described in the following section.

2.3.2 Char combustion reactivity in synthetic air: The methodology used by Cousins *et al.* (2006 a, b) has been applied to CAZ1 and CAZ2 char samples produced in the TF and in the HRR at 500 °C. A standard isothermal TGA test using a TGA Q 500 (TA Instruments Inc.) was applied to samples of (1.5-3.0) mg. Analysis steps: (1) equilibrium at 50 °C under N_2, isotherm for 1 min; (2) heating at 40 °C.min^{-1} to 110 °C under N_2 at 40 mL.min^{-1} and isotherm for 10 min (moisture content); (3) heating at 40 °C.min^{-1} to 500 °C and weight stabilisation (VM content); (4) swicht from N_2 to air; (5) hold under previous conditions until at least 50% of the sample had reacted; (6) heating at 20 °C.min^{-1} to 850 °C to combust the remaining sample and isotherm for additional 5 min (ash content). Weight losses were recorded continuously and the char conversion (*X*) and char reactivity (*r*) were calculated by applying the equations (2) and (3).

$$X = \left(\frac{m_0 - m}{m_0} \right) \tag{2}$$

$$r = -\frac{1}{m_0} \left(\frac{dm}{dt} \right) \tag{3}$$

Where *r* is the reactivity (given in mg.mg^{-1}.min^{-1}), m_0 is the initial weight of the char sample (daf basis) for the combustion step, *m* is the instantaneous sample mass (daf basis) and (*dm/dt*) is the rate of weight loss. Only single determinations have been reported, being the repeatability of *r* determination ±9% of the value quoted.

2.3.3 Char gasification reactivity in CO_2: The experiments were carried out in a thermogravimetric analyser (model DTG 60, Shimadzu) in CO_2 atmosphere at (850-950) °C with

CAZ1 and CAZ2 ((22-27) mg, (106-150) µm, moisture content of 8.71 wt% and 9.00 wt%, respectively). The pyrolysis step was performed in the proper thermogravimetric analyser as a step previous to char gasification. Analysis steps: (1) purge with N_2 at 100 mL.min^{-1} and 35 °C for 60 min; (2) heating at 50 °C.min^{-1} to 110 °C under N_2 at 100 mL.min^{-1} and isotherm for 5 min; (3) pyrolysis step: heating at 50 °C.min^{-1} to 850 °C under N_2 at 100 mL.min^{-1} and isotherm for 15 min; (4) heating at 50 °C.min^{-1} up to the reaction temperature (837 °C, 888 °C, 912 °C or 936 °C) under N_2 at 100 mL.min^{-1}; (5) gasification step: swicht from N_2 to CO_2 at 100 mL.min^{-1}, with isotherm for 120 min. The comparison of the char samples reactivity in CO_2 (both prepared at 850 °C) was only made for the gasification temperature of 837 °C in order to check whether the difference observed for the char reactivity in synthetic air at 500 °C (chars produced at pyrolysis temperature of 500 °C) also occurred in these conditions. The data aquisition was initiated after the purge step was complete. In order to obtain preliminary information about the CO_2 gasification potential of CAZ1 char, it has been analysed in the same conditions previously described at three additional gasification temperatures: 888 °C, 912 °C and 936 °C. The degree of carbon conversion (*X*) and the reactivity (*r_c*) in terms of carbon content for gasification with CO_2 was determined by applying equations (2) and (3) to the data obtained from TGA runs, being m_0 the initial mass of carbon (determined by elemental analysis) in the char sample, *m* the instantaneous mass of carbon in the char sample, and *dm/dt* the rate of carbon mass loss. The activation energy (*E_a*) in CO_2 gasification was calculated by plotting *ln r_{cmax}* as a function of (*1/T*) for the Arrhenius equation (4):

$$r_{cmáx} = k_0 . \exp\left(\frac{-E_a}{RT} \right) \qquad (4)$$

Where r_{cmax} is the maximum reactivity (mg.mg^{-1}.min^{-1}) measured during the gasification of the carbon present in the char sample in a given reaction temperature, k_0 is the pre-exponential factor (min^{-1}), E_a is the activation energy (J.mol^{-1}), *R* is the gas constant (8,314 J.mol^{-1}.K^{-1}) and *T* the absolute temperature (K). This method is applied to the results obtained under the chemically controlled regime. The transition from the chemical to the diffusion-controlled regime can be detected from the change in the slope on the Arrhenius plot.

2.3.4 SEM/EDS analysis: The char samples produced from CAZ1 and CAZ2 in the TF and in the HRR at 500 °C were analised using a Scanning Electron Microscope (SEM) (model TM-1000, Hitachi) equipped with an Energy Dispersive X-ray Spectrometer (EDS) (model SwiftED-TM, Hitachi). The char samples produced from CAZ1 and CAZ2 in the TF at 850 °C were analised using a Scanning Electron Microscope (SEM) (model EDAX DX-4/EDS, Phillips).

2.3.5 Trace elements analysis: Cu, Mg, Mn, Be, Co, Mo, V, Cr, As, Cd, Ni and Zn in the char samples have been quantified by Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) after digestion by nitric acid in a closed bomb within a microwave oven in order to investigate possible catalytic effects on the char reactivity. Details of trace element quantification have been presented elsewhere (Richaud *et al.*, 1998; Richaud *et al.*, 2000; George *et al.*, 2008).

3. RESULTS AND DISCUSSION

3.1. Biomass properties

Table 2 – Biomass properties

Biomass	CAZ1	CAZ2
Proximate analysis		
A[a] (%, db[b])	13.43	16.80
VM[c] (%, daf[d])	76.19	77.54
FC[e] (%, daf)	23.81	22.46
M[f] (%, ar[g])	6.89	10.10
Ultimate analysis		
C (%, daf)	43.14	46.98
H (%, daf)	5.57	5.86
N (%, daf)	0.36	0.80
S (%, daf)	<0.01[h]	0.05
O[i] (%, daf)	50.91	45.95
Cl (%, daf)	0.02	0.36
Heating value (MJ.kg^{-1})		
HHV[j] (daf)	19.06	19.93
LHV[k] (daf)	17.59	17.79

[a] Ash; [b] Dry basis; [c] Volatile matter; [d] Dry and ash free basis; [e] Fixed carbon; [f] Moisture; [g] As received; [h] Not quantifiable, lower limit of quantification equal to 0.01%; [i] Value obtained by difference; [j] Higher heating value; [j] Lower heating value.

3.2. Pyrolysis experiments

The pyrolysis experiments at 500 °C in the TF presented the best results in terms of low char yield comparatively to the other temperatures tested. CAZ2 produced a relatively low amount of tar and a relatively high amount of volatiles in the HRR, which implies that it may be the most promising feed of the suite tested as a gasification feedstock. Venderbosch and Prins (2010) discussed the effects of ash properties on biomass pyrolysis, suggesting that high ash content favours charring reactions, which increases char yield. CAZ1 and CAZ2 contained 13.43 wt% and 16.80 w% (db) ash, respectively. The order of the amounts of ash corresponds to the amounts of solid residue (char and ash) produced. Hence it appears that the larger the amount of ash, the larger the amount of char produced. However, as the ash content increases, the C content falls so that the quality of the char (in terms of energy content) falls. Therefore, although a high ash content sample produces more char, the quality of the char produced may not be very good. The total amount of recovered products (tar and chars) was higher than 61% of the original biomass for the two rice husk samples. Comparison with the char yield from the tubular furnace indicates that there was significantly more char remaining when the material was studied in the HRR. This may be due to the higher pressure required in the HRR. The amounts of CH_4, CO and CO_2 released by CAZ1 (0.2%, 1.4%, 4.0%, respectively) in the HRR at 500 °C were slightly higher than the amounts released by CAZ2 (0.1%, 1.1%, 3.5%, respectively).

3.3. Pyrolysis char properties

3.1.1 Proximate and ultimate composition: Table 3 presents the results for the samples prepared in the TF and HRR. C, H, N were determined only for the runs at 500 °C and 850 °C.

3.1.2 Char combustion reactivity in synthetic air: The maximum combustion reactivity (r_{max}) at 500 °C was higher (0.312 mg.mg^{-1}.min^{-1} for CAZ1 and 0.760 mg.mg^{-1}.min^{-1} for CAZ2) for the chars produced at 500 °C in the TF compared to the three other pyrolysis temperatures.

Table 3 – Char properties

Biomass	T^a	M^b	VM^c	A^d	FC^e	C	H	N
	(°C)	(wt%, db)	(wt%, db)	(wt%, db)	(wt%, db)	(wt%, db)	(wt%, db)	(wt%, db)
Tube furnace								
CAZ1	350	0.66	26.28	26.98	46.74	n.d.^{f}	n.d.	n.d.
CAZ1	500	2.15	6.48	40.15	53.37	43.48±0.21	2.58±0.21	0.83±0.07
CAZ1	700	0.32	1.89	46.00	52.11	n.d.	n.d.	n.d.
CAZ1	850	1.13	5.77	46.79	47.44	47.35±0.21	1.72±0.21	0.80±0.07
CAZ2	350	1.16	22.64	31.47	45.99	n.d.	n.d.	n.d.
CAZ2	500	1.22	6.85	42.54	50.62	45.03±0.21	2.57±0.21	0.81±0.07
CAZ2	700	1.74	2.92	46.57	50.52	n.d.	n.d.	n.d.
CAZ2	850	1.05	2.76	47.84	49.40	42.05±0.21	1.45±0.21	0.50±0.07
Hot-rod reactor								
CAZ1	500	3.29	8.78	35.53	55.69	49.48±0.21	2.85±0.21	1.15±0.07
CAZ2	500	3.07	9.60	33.46	56.94	35.58±0.21	2.19±0.21	0.55±0.07

[a] Pyrolysis temperature; [b] Moisture; [c] Volatile matter; [d] Ash; [e] Fixed carbon; [f] Not determined.

The reason for the decrease in char reactivity with the increase in pyrolysis temperature may be due to the increased structural ordering of the carbon matrix, which has the effect of reducing the concentration of reaction sites, such as suggested by Kumar and Gupta (1994). The r_{max} of CAZ2 was 2-5 times higher than the value found for CAZ1 char at all pyrolysis temperatures in the TF. Comparing CAZ1 and CAZ2 chars produced in the HRR at the same pyrolysis conditions, the r_{max} was also achieved for the Thai rice husk char, being almost two times higher (0.518 mg.mg^{-1}.min^{-1}) than the value found for CAZ1 char (0.315 mg.mg^{-1}.min^{-1}). Comparing the two reactors, the r_{max} of CAZ1 char at 500 °C was similar (0.312 mg.mg^{-1}.min^{-1} for TF, and 0.315 mg.mg^{-1}.min^{-1} for HRR). For CAZ2, on the other hand, the r_{max} of the char produced in the TF was 46.7% higher compared to the one produced in the HRR. According to Ollero *et al.* (2003) and Cetin *et al.* (2004), this can be attributed, in part, to the higher pressure applied during pyrolysis in the HRR (2.2 bar).

3.1.3 Char gasification reactivity in CO_2: The maximum gasification reactivity (r_{cmax}) of CAZ2 char (0.013 mg.mg^{-1}.min^{-1}) was slightly higher than CAZ1 char (0.008 mg.mg^{-1}.min^{-1}), thus confirming the trend observed for reactiviy in air at 500 °C. Besides gasification at 837 °C, three other gasification temperatures were applied to CAZ1 char: 888 °C, 912 °C, 936 °C. The total mass loss percentage of approximately 76 wt% was achieved in the pyrolysis step, which corresponds to the VM of CAZ1. The higher conversion was reached at 912 °C (X_c=0.57), followed by 888 °C (X_c=0.54), 936 °C (X_c=0.52) and 837 °C (X_c=0.47). However, the reaction rate was higher at 936 °C, being complete in approx. 50 min. As expected, the r_{cmax} for CAZ1 were essentially dependent on the final heat treatment temperature due to the significant improvement in internal surface area during gasification and/or the catalysis of mineral impurities which become more effective at relatively high temperatures, with higher values occurring at the higher temperature applied (936 °C). It is known that the rate of gasification depends on the accessibility of the reactant gas to the internal surface of porous char where active sites reside. The experimental data was satisfactorily represented by the proposed equations, thus indicating that the reaction kinetics at the temperatures studied were in the chemical reaction control region. E_a was equal to 72.91 kJ.mol^{-1}, value which is in the range found in the literature (70-220 kJ.mol^{-1}) (Ollero *et al.*, 2003; Fermoso *et al.*, 2009; Link *et al.*, 2010). The k_0 obtained was 24.32 min^{-1}.

3.1.4 Trace elements and SEM/EDS analyses: CAZ1 chars (TF and HRR) contained

scale. *Ind. Eng. Chem. Research*, v. 38, p. 2571–2581, 1999.

DIN 51718 – Testing of solid fuels e determination of the water content and the moisture of analysis sample, June 1, 2002.

DIN 51719 – Testing of solid fuels e solid mineral fuels e determination of ash content, July 1, 1997.

DIN 51720 – Testing of solid fuels e determination of volatile matter content, March 1, 2001.

DIN 51900-1 – Determining the gross calorific value of solid and liquid fuels using the bomb calorimeter, and calculation of net calorific value e part 1: general information, 2000.

DIN 51900-3 – Testing of solid and liquid fuels e determination of gross calorific value by the bomb calorimeter and calculation of net calorific value e part 3: method using adiabatic jacket, 2005.

FERMOSO, J.; STEVANOV, C.; MOGHTADERI, B.; ARIAS, B.; PEVIDA, C.; PLAZA, M.G.; RUBIERA, F.; PIS, J.J. High-pressure gasification reactivity of biomass chars produced at different temperatures. *J. Anal. Appl. Pyrolysis*, v. 85, p. 287-293, 2009.

GEORGE, A.; DUGWELL, D.R.; KANDIYOTI, R. Development of a miniaturized technique for measuring the leachability of toxic trace elements from coal-biomass co-combustion ash residues. Energy *Fuels*, v. 21(2), p. 728-734, 2008.

GUERRERO, M.; RUIZ, M.P.; ALZUETA, M.U.; BILBAO, R.; MILLERA, A. Pyrolysis of eucalyptus at different heating rates: studies of char characterization and oxidative reactivity. *J. Anal. Appl. Pyrolysis*, v. 74, p. 307-314, 2005.

KUMAR, M.; GUPTA, R.C. Influence of carbonization conditions on the gasification of acacia and eucalyptus wood chars by carbon dioxide. *Fuel*, v. 73(12), p. 1922-1925, 1994.

LINK, S.; ARVELAKIS, S.; HUPA, M.; YRJAS, P.; KÜLAOTS, I.; PAIST, A. Reactivity of the biomass chars originating from reed, douglas fir, and pine. *Energy Fuels*, v. 24, p. 6533-6539, 2010.

MANSARAY, K.G.; GHALY, A.E. Determination of kinetic parameters of rice husks in oxygen using thermogravimetric analysis. *Biomass and Bioenergy,* v. 17, p. 19-31, 1999.

MANSARAY; K.G.; GHALY, A.E.; AL-TAWEEL, A.M.; HAMDULLAHPUR, F.; UGURSAL, V.I. Air gasification of rice husk in a dual distributor type fluidized bed gasifier. *Biomass and Bioenergy,* v. 17, p. 315-332, 1999.

OLLERO, P.; SERRERA, A.; ARJONA, R., ALCANTARILLA, S. The CO_2 gasification kinetics of olive residue. *Biomass and Bioenergy*, v. 24(2), p. 151-161, 2003.

PINDORIA, R.V.; MEGARITIS, A.; MESSENBÖCK, R.C.; DUGWELL, D.R.; KANDIYOTI, R. Comparison of the pyrolysis and gasification of biomass - effect of reacting gas atmosphere and pressure on Eucalyptus wood. *Fuel,* v. 77(11), p. 1247-1251, 1998.

RAVEENDRAN, K.; GANESH, A. Adsorption characteristics and pore development of biomass pyrolysis char. *Fuel*, v. 77, p. 769-781, 1998.

RICHAUD, R.; LACHAS, H., COLLOT, A.G.; MANNERINGS, A.G.; HEROD, A.A.; DUGWELL, D.R.; KANDIYOTI, R. Trace mercury concentrations in coals and coal-derived material determined by atomic absorption spectrophotometry. *Fuel*, v. 77, p. 359-368, 1998.

RICHAUD, R.; LACHAS, H., HEALEY, A.E.; REED, G.P.; HAINES, J.; MASON, P., HEROD, A.A.; DUGWELL, D.R.; KANDIYOTI, R. Trace element analysis of gasification plant samples by ICP-MS: validation by comparison of results from two laboratories. *Fuel*, v. 79, p. 1077-1087, 2000.

VENDERBOSCH, R.H.; PRINS, W. Review: Fast pyrolysis technology development. *Biofuels, Bioproducts & Biorefining*, v. 4, p. 178-208, 2010.

VIRMOND, E. Utilização de resíduos agroindustriais como fonte alternativa de energia. Tese de Doutorado. Universidade Federal de Santa Catarina, UFSC. Florianópolis, SC, Brasil. 2011. 265 p.

ZOLIN, A.; JENSEN, A.; JENSEN, P.A.; FRANDSEN, F.; DAM-JOHANSEN, K. The influence of inorganic materials on the thermal deactivation of fuel chars. *Energy Fuel*, v. 15, p. 1110-1122, 2001.