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Hydrogen production from high temperature steam catalytic gasification of bio-char

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ABSTRACT: Hydrogen production from the catalytic steam gasification of bio-char derived from the pyrolysis of sugar cane bagasse has been investigated in relation to gasification temperature up to 1050 °C, steam flow rate from 6 to 25 ml h⁻¹ and type of Nickel catalyst. The catalysts used were Ni-dolomite, Ni-MgO and Ni-Al₂O₃, all with 10% nickel loading. The hydrogen yield in the absence of a catalyst at a gasification temperature of 950 °C was 100.97 mmol. g⁻¹ of bagasse char. However, the presence of the Ni-MgO and Ni-Al₂O₃ catalysts produced significantly improved hydrogen yields of 178.75 and 187.25 mmol. g⁻¹ of bagasse char respectively at 950 °C. The hydrogen yield from the char with the Ni-dolomite only showed a modest increase in hydrogen yield. The influence of gasification temperature showed that the optimum temperature to obtain the highest hydrogen yield was 950 °C. Increase in gasification temperature from 750 to 950 °C significantly increased hydrogen yield from 45.30 to 187.25 mmol. g⁻¹ of bagasse char at 950 °C, but was followed by a decrease in yield at 1050 °C. The influence of steam flow rate showed that with the increase in steam flow rate from 6 to 15 ml h⁻¹ hydrogen yield was increased from 187.25 to 208.41 mmol. g⁻¹ of bagasse char. Further increase in steam flow rate resulted in a decrease in hydrogen yield.

Keywords: Gasification; biomass; hydrogen; catalyst; bio-char

1. Introduction

Energy recovery from different types of waste biomass such as agricultural waste, food manufacture waste and forestry residues is gaining interest due to concerns about the limited supply of fossil fuels and the environmental impact from fossil fuel use. Sugar cane (*saccharum officinarum*) bagasse is a fibrous material which occurs as a by-product of sugar manufacture and it is estimated that 180 million tonnes of sugar cane bagasse is generated each year.¹ Such large tonnages of waste biomass have the potential to be used for a range of energy conversion processes with the added benefit of mitigating against climate change problems.

Pyrolysis is amongst the thermochemical processes commonly used to recover energy from biomass. In the case of pyrolysis of biomass, a bio-oil product is generated with by-product bio-char also formed in addition to pyrolysis gases. The relative proportion of bio-char, bio-oil and gases depends on the process conditions such as temperature and heating rate. There is growing interest in the production of hydrogen from biomass since it is regarded as a clean, low carbon future source of energy.^{2,3} Steam gasification of bio-char produces a syngas with a high hydrogen content and higher calorific value.⁴ It has been reported that the steam gasification of bio-char is 2 - 3 times faster as compared to coal gasification.⁵

Several researchers have investigated different aspects of bio-char gasification.⁴⁻¹⁴ Many studies have focused on oxidation of bio-char using thermogravimetric analysis (TGA). For example Luo et al.⁶ and Maiti et al.⁸ studied the kinetics of bio-char using TGA. Some authors have investigated the mechanism of char gasification. For example, Moilanen et al.⁷ reported that the gasification of solid char particles starts by the diffusion of the gasifying agent to the particle surface and then to the inside of the particle resulting in adsorption onto the surface followed by the chemical reaction. Haykiri-Acma et al.⁹ suggested that the high

temperature steam gasification of char is recommended for the production of hydrogen as the mechanism of gasification varies with the temperature and hydrogen production is favoured at high temperature.

In this paper, hydrogen production from the steam catalytic gasification of bio-char in a high temperature fixed bed reactor has been investigated. The influence of process operating parameters such as catalyst, gasification temperature and steam flow rate were researched. The influence of three different catalysts; 10 wt.% Ni-dolomite, 10 wt.% Ni-Al₂O₃ and 10 wt.% Ni-MgO on H₂ production at a temperature of 950 °C was investigated. The influence of gasification temperature (750 – 1050 °C) and steam flow rate (6 - 25 ml h⁻¹) on H₂ yield was also investigated.

2. Materials and methods

2.1. Bio-char samples

Pyrolysis char recovered from the pyrolysis of sugar cane bagasse was used in this study.¹⁵ The properties of the feedstock sugar cane bagasse used for pyrolysis are shown in Table 1. The sugar cane bagasse was sourced from Pakistan and obtained from fields near Samundri (30 48 N 71 52 E). These fields supply sugar cane to Gojra Samundri Sugar Mills Limited. Pakistan is the fifth largest sugar cane producer in the world with an estimated 49 million tonnes of sugar cane produced annually resulting in 16 million tonnes of bagasse in the form of residue from the sugar industry. The sugar cane bagasse biomass sample was pyrolysed in a fixed bed reactor in an inert atmosphere of nitrogen and was heated from ambient temperature to a temperature of 950 °C at a constant heating rate of 20 °C min⁻¹ with a dwell

time of 40 minutes at 950 °C. The char samples were ground and sieved to obtain a particle size in the range of 0.2 – 0.5 mm.

2.2. Catalyst

Three different catalysts; 10 wt.% Ni-dolomite, 10 wt.% Ni-Al₂O₃ and 10 wt.% Ni-MgO were used in this study. These catalysts were synthesised in the laboratory using a wet impregnation method;¹⁶ a known quantity of Ni(NO₃)₂.6H₂O was dissolved in 25 ml of deionized water; 10 g of support material (dolomite, Al₂O₃ or MgO) was then mixed in the solution and heated up to 105 °C with constant stirring. Each catalyst was dried overnight at 105 °C and then calcined at 900 °C for 3 hours in an air atmosphere. These catalysts were later ground and sieved to achieve a final particle size between 0.050 - 0.212 mm.

2.3. Material characterization

A Thermoquest CE Flash EA 2000 series instrument was employed for C, H, N and S analysis of the bio-char (Table 2). Proximate analysis was carried out on a Shimadzu TGA-50H thermogravimetric analyser. In addition, ashing of the bio-char sample was carried out and the residual ash was analysed using an Olympus Innovex X-5000 X-ray Fluorescence (XRF) equipped with a Rh source to determine the bulk metal composition.

The freshly prepared catalysts were characterised using a range of techniques. The surface area (BET (Brunauer, Emmett and Teller)), pore volume, and pore size distribution of the fresh catalysts was determined using a Nova-2200e surface area and pore size analyser from Quantachrome instruments USA.

The surface morphology of the catalyst was determined using scanning electron microscopy. The system used was a Field Emission Gun Scanning Electron Microscope (FEGSEM) LEO 1530 equipped with 80mm X-Max SDD detector.

2.4. Experimental reactor

Steam gasification of the bio-char recovered from the pyrolysis of sugar cane bagasse was carried out in a high temperature fixed bed reactor system, 60 cm in length with 2.5 cm inner diameter and constructed of Inconel (Figure 1). Nitrogen was used as the purge gas. During this study, the bio-char sample was gasified (with and without catalyst) in the presence of steam at high temperature of 950 °C, this high temperature was chosen, since literature data suggests that higher temperatures of char gasification produce higher yields of H₂.^{9, 15} In addition, the influence of gasification temperature on the catalytic steam gasification of the bio-char was also investigated at temperatures of, 750, 850, 950, and 1050 °C. During the catalytic steam gasification of the sugar cane bagasse bio-char samples, the Ni-dolomite, Ni-Al₂O₃ and Ni-MgO catalysts were used. The catalyst was mixed with the bio-char sample (catalyst to sample ratio of 1:1) and then placed on a perforated mesh inside the reactor. The reactor was then heated from room temperature to a temperature of 950 °C at a constant heating rate of 20 °C min⁻¹, with a continuous purge of nitrogen. Once the reactor reached the required temperature, steam was introduced into the reactor via water injected from a syringe pump which was immediately converted into steam at high temperature and swept through the reactor by the nitrogen carrier gas. For all experiments, the steam flow rate was constant at 6 ml h⁻¹ except when the influence of steam flow rate was investigated where steam flow rates from 6 to 25 ml h⁻¹ were used. Product volatiles and excess steam were condensed in a series of condensers. The non-condensable gases were collected using a TedlarTM gas sample bag and were analysed offline using gas chromatography.

2.5. Gas analysis

Two different gas chromatographs (GC's) were used to analyse the gas samples collected in the gas sample bag. The gases were analysed for hydrocarbons (C₁-C₄) using a Varian CP-3380 gas chromatograph with a column packed with an 80-100 mesh HayeSep with a flame

ionization detector (GC/FID) and using N₂ as carrier gas. Permanent gases (H₂, CO, N₂, O₂, CO₂) were analysed using a second Varian CP-3380 chromatograph comprised of two columns with two thermal conductivity detectors (GC/TCD). One column packed with a 60-80 mesh molecular sieve, was used to separate H₂, CO, N₂, O₂; and the other column was packed with 80-100 mesh HayeSep was used to analyse CO₂; the carrier gas used was argon.

3. Results and Discussion

3.1 Bio-char and catalyst characteristics

The bio-char produced from the pyrolysis of sugar cane bagasse (Table 2) represented ~25% of the original biomass which contained 45.5 wt.% carbon. The char analysis showed a carbon content of 81.55 wt.% representing around 50 % of the carbon contained in the original biomass sample was still present in the bio-char. The amount of residual ash in the char was 9.44 wt.% for the bagasse char. The results of XRF analysis of the ash (Table 2) showed a significant quantity of SiO₂ and ~10 % Al₂O₃ was present in ash from bagasse and a significant quantity of CaO and K₂O was also present.

The surface characteristics of the prepared 10 wt.% Ni-dolomite, 10 wt.% Ni-Al₂O₃ and 10 wt.% Ni-MgO catalysts in terms of surface area and porosity characteristics are shown in Table 3. The BET surface area for the Ni-dolomite catalyst at 5.56 m² g⁻¹, was significantly lower than that of the Ni-MgO and Ni-Al₂O₃ catalysts which showed a BET surface area of 53.90 and 76.82 m² g⁻¹ respectively. In addition, the average pore size of the Ni-MgO catalyst at 36.08 nm was significantly larger than the Ni-dolomite catalyst and the Ni-Al₂O₃ catalyst which showed an average pore size of 2.21 nm and 5.64 nm respectively.

Figure 2 shows SEM micrographs from the scanning electron microscope analysis of the fresh prepared Ni-dolomite, Ni-Al₂O₃ and Ni-MgO catalysts. The Ni-dolomite catalyst has a

nodular structure, the Ni-Al₂O₃ appears more smooth and the Ni-MgO catalysts shows a plate-like structure with small nodules.

3.2. The influence of different catalysts on hydrogen production from gasification of sugar cane bagasse char at 950 °C

3.2.1. Product yield

The three different catalysts; 10 wt.% Ni-MgO, 10 wt.% Ni-Al₂O₃ and 10 wt.% Ni-dolomite were mixed with the bagasse char sample and gasified in the presence of steam at 950 °C and compared with gasification in the absence of any catalyst. Gas yield and H₂ yield results are shown in Table 4. As ~25% of bio-char was obtained from the pyrolysis of sugar cane bagasse, H₂ yield results are presented in Table 4, as mmol. g⁻¹ of char and also as mmol. g⁻¹ of biomass.

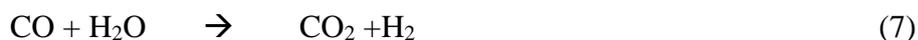
From the results shown in Table 4, it is clear that the presence of catalyst significantly improved the H₂ yield during gasification. When compared with the steam gasification without any catalyst, use of the Ni-dolomite slightly improved the H₂ yield from 100.97 mmol. g⁻¹ to 112.36 mmol. g⁻¹ of char. However, the Ni-MgO and Ni-Al₂O₃ catalyst gave a marked increase in H₂ yield, the addition of the Ni-MgO catalyst showed an increase of 78 % H₂ as compared to no catalyst. The highest H₂ yield of 187.25 mmol. g⁻¹ of char was obtained when the bagasse char was mixed with the Ni-Al₂O₃ catalyst. It is suggested that higher H₂ yield obtained using the Ni-MgO and Ni-Al₂O₃ catalysts was most likely due to the higher surface area of these two catalysts at 53.90 and 76.82 m² g⁻¹ respectively (indicating higher dispersion of metals on the surface of the catalyst). The Ni-MgO and Ni-Al₂O₃ catalysts also had significantly high pore volume compared to the Ni-dolomite catalyst (Table 3).

The catalytic role of various alkali and alkaline earth metals has been reported in the literature. For example, Maiti et al.¹⁰ investigated the steam gasification of a char sample obtained from the pyrolysis of cedar and bamboo biomass. The comparison of as-received char and acid-washed char revealed that the presence of alkali and alkaline earth metals, especially potassium, strongly influenced the conversion and reactivity of char samples by catalysing the various char conversion reactions. Otto et al.¹⁷ also confirmed the catalytic effect of various metals such as Pt, Rh, Ru and Pd. They reported that the addition of these catalysts strongly enhanced the gasification rate. The bio-char contained significant ash content at 9.44 wt.% and Table 2 shows that the ash contained alkali and alkaline earth metals, including CaO and K₂O, adding to the catalytic activity of the added Ni-dolomite, Ni-MgO and Ni-Al₂O₃ catalysts.

3.2.2. The influence of different catalysts on gas composition and hydrogen production

The influence of catalyst on the product gas composition obtained from the steam catalytic gasification of sugar cane bagasse char was determined and the product gas composition results are shown in Figure 3. The results indicate that the presence of catalyst significantly improved the product gas composition in terms of H₂ production. The concentration of H₂ was slightly improved from 57.74 vol.% with no catalyst to 60.54 vol.% for the Ni-dolomite catalyst. Use of Ni-MgO enhanced the H₂ concentration to 73.30 vol.%. The highest H₂ concentration of 76.81 vol.% was obtained when the Ni-Al₂O₃ catalyst was used during gasification. The gasification of bio-char was strongly influenced by the presence of catalysts and it is suggested that these catalysts influenced the chemical equilibria of the various reactions taking place inside the gasifier. Yang et al.¹⁸ also reported that the H₂ concentration was increased up to 1.8 times with the use of Au/Al₂O₃ catalyst during the steam gasification of char derived from the pyrolysis of biomass. Different chemical reactions taking place during the steam gasification of biomass char are shown in equations (1) to (7). It is evident

that the addition of steam favoured oxidation reactions (Equation (1) – (2)) and water gas reactions (Equation (3) – (4)).



As shown in Figure 3, the highest concentration of H₂ (76.81 vol.%) was achieved with the use of the Ni-Al₂O₃ catalyst while a significant reduction in the concentration of CO from ~25 vol.% for no catalyst to ~15 vol.% for the Ni-Al₂O₃ catalyst was observed. It is suggested that the presence of Ni-Al₂O₃ improved the H₂ concentration by altering the equilibrium of the water-gas shift reaction (Equation (7)). As shown in Table 4, the H₂:CO ratio was increased from 2.31 for no catalyst to 3.58 for the Ni-MgO catalyst and to 5.00 for the Ni-Al₂O₃ catalyst. The concentration of CO₂ was also sharply reduced from 17.05 vol.% for no catalyst to 7.67 vol.% with the Ni-Al₂O₃ catalyst and to 4.77 vol.% with the Ni-MgO catalyst. It is suggested that the higher gasifier temperature promoted the endothermic Boudouard reaction (Equation (5)) resulting in reduction of CO₂ concentration. The CO:CO₂ ratio was increased from 1.47 for no catalyst to 4.29 for the Ni-MgO catalyst. The presence of catalyst does not appear to have any influence on the methanation reaction (Equation (6)) as the

concentration of methane in the product gaseous mixture was almost constant at ~ 0.14 vol.% during all experiments.

3.3. The influence of temperature on char gasification

3.3.1. Product yield

The influence of char gasification temperature was investigated for the catalytic steam gasification of sugar cane bagasse char with the 10 wt.% Ni-Al₂O₃ catalyst only. The char sample was mixed with the Ni-Al₂O₃ catalyst and placed inside the gasifier. The sample was heated to the desired temperature of 750, 850, 950 or 1050 °C in nitrogen, then when the temperature was attained, steam was introduced. The results showing the influence of gasification temperature on gas yield and H₂ yield are shown in Table 5. It is evident from Table 5 that with the increase in gasification temperature from 750 to 1050 °C H₂ yield was significantly increased.

When the temperature was increased from 750 to 850 °C, the H₂ yield sharply increased from 45.30 to 120.84 mmol. g⁻¹ of bagasse char. Further increase in temperature to 950 °C resulted in a further significant increase in H₂ yield to 187.25 mmol. g⁻¹ of char with a small decrease in H₂ yield as the temperature was increased to 1050 °C. The increase in H₂ yield with the increase in gasification temperature is related to the various endothermic reactions such as water gas reactions (Equation (3) and Equation (4)) and Boudouard reaction (Equation (5)) which were favoured at higher temperature.

The increase in gasification temperature producing enhanced carbon conversion has been reported in the literature. For example, Yan et al.¹² reported that with the increase in gasification temperature from 600 to 850 °C, char carbon conversion significantly increased during the steam gasification of pine sawdust char. An increase in conversion rate of

biomass-derived char during steam gasification was also reported by Nanou et al.¹⁹ They achieved 95 % conversion within 4.1 min at 800 °C as compared to 40 % conversion at 600 °C after 17.5 minutes. An increase in carbon conversion with increase in temperature was also reported by Encinar et al.⁴

A slight reduction in H₂ yield when the temperature was increased from 950 to 1050 °C which was most likely due to the reverse water-gas shift reaction (Equation (7)); since the water gas shift reaction is slightly exothermic and is not favourable at high temperature (1050 °C) for the production of H₂. A decrease in H₂:CO ratio from 5 to 4.06 was observed with the increase in temperature from 950 to 1050 °C.

3.3.2. The influence of temperature on gas composition and hydrogen production

The influence of gasification temperature on product gas composition (Figure 4) indicate that with the increase in temperature, H₂ concentration in the gas mixture was improved, increasing from 67.76 vol.% at 750 °C to 76.81 vol.% at 950 °C. Further increase in gasification temperature to 1050 °C, resulted in a slight reduction of H₂ concentration to 69.68 vol.%. Yan et al.¹² reported that with the increase in gasification temperature, the H₂ concentration in the gas mixture was increased from 29.54 vol.% at 600 °C to 52.41 vol.% at 850 °C.

With the increase in temperature, the concentration of CO was increased from 8.16 to 17.14 vol.% while the concentration of CO₂ was reduced from 23.71 vol.% at 750 °C to 10.86 vol.% at 1050 °C. The reduction in CO₂ concentration was mainly attributed to the Boudouard reaction and dry reforming reactions. As shown in Table 5, the increase in CO:CO₂ ratio from 0.34 at 750 °C to 1.58 at 1050 °C suggests that the Boudouard reaction was favoured. The increase in CO concentration with the rise in temperature may be attributed to several endothermic reactions such as oxidation reactions, water gas reaction and

Boudouard reaction. A decrease in H₂:CO ratio from 5 at 950 °C to 4.06 at 1050 °C suggests that the reverse water-gas shift reaction might have contributed towards the higher CO concentration at 1050 °C. Howaniec et al.¹⁴ reported an increase in H₂ and CO concentrations with the rise in temperature from 700 to 900 °C during the steam gasification of biomass char. With the increase in temperature, the concentration of H₂ was increased from 60 to 64 vol.% while the CO concentration was increased from 8 to 10 vol.% with the reduction in CO₂ concentration from 31 vol.% at 700 °C to 26 vol.% at 900 °C. Umeki et al.²⁰ also recommended higher gasification temperature of 900 °C for higher H₂ yield.

3.4. The influence of steam flow rate on char gasification

3.4.1. Product yield

In order to enhance the H₂ yield from steam gasification of biomass char, the influence of steam flow rate was investigated. Four different steam flow rates of 6, 15, 20 and 25 ml h⁻¹ were investigated and experiments were carried out in the presence of the 10 wt.% Ni-Al₂O₃ catalyst only. The H₂ yield and mass balance results are shown in Table 6. These results indicate that with the initial increase in steam flow rate from 6 to 15 ml h⁻¹ the H₂ yield was increased from 187.25 to 208.41 mmol. g⁻¹ of biomass char. However further increase in steam flow rate resulted in a decrease in H₂ yield to 168.58 mmol. g⁻¹ char for 20 ml h⁻¹ and to 174.20 mmol. g⁻¹ char for 25 ml h⁻¹ steam flow rate.

It is suggested that the initial increase in H₂ yield was due to the promotion of the water gas and the water gas shift reactions. Further increase in steam flow rate led to a decrease in H₂ concentration due to the fact that the amount of char available was not sufficient for the amount of injected steam. Similar findings were reported by Yan et al.¹² They investigated the influence of steam flow rate on gasification of pine sawdust char at 850 °C. It was reported that initially with the increase in steam flow rate from 0 to 0.165 g min⁻¹ g⁻¹ of

biomass char, H₂ yield increased from 2.15 mol. kg⁻¹ to 57.07 mol. kg⁻¹. Further increase in steam flow rate to 0.357 g min⁻¹ g⁻¹ of biomass char resulted in a decrease in H₂ yield to 37.47 mol. kg⁻¹.

By increasing the steam flow rate during gasification, extra oxygen and hydrogen was made available into the system. Furthermore at high temperatures such as the 950 °C used in this work, by increasing the steam flow rate, the equilibrium of the water-gas shift reaction may enhance the H₂ yield. Paviet et al.⁵ investigated the kinetics of the steam gasification of wood char. They performed char gasification in a tubular kiln reactor at various temperatures and steam flow rates. It was observed that with the increase in steam molar fraction, the char consumption rate was increased due to the lower diffusion resistance at higher steam flow rates.

3.4.2. The influence of steam flow rate on gas composition and hydrogen production

The influence of an increase in steam flow rate on product gas composition is shown in Figure 5. It was observed that under the experimental conditions used, steam flow rate was inversely proportional to the H₂ concentration in the product gas mixture. It was observed that with the increase in steam flow rate, the concentration of H₂ was slightly reduced from 76.81 vol.% for 6 ml h⁻¹ steam flow rate to 73.95 vol.% for a steam flow rate of 15ml h⁻¹. There was no further change in H₂ concentration with the increase in steam flow rate to 20 and to 25 ml h⁻¹.

The concentration of CO₂ gradually increased from 7.67 to 14.13 vol.% with the increase in steam flow rate. Yan et al.¹² also reported an increase in CO₂ concentration with the increase in steam flow rate. The concentration of CO was almost constant at ~15 vol.%. It is suggested that the increase in steam flow rate favoured the oxidation of char and CO which caused the increase in CO₂ concentration. Although it was speculated that the increase in

steam flow rate would favour the water gas shift reaction towards H₂ formation a decrease in H₂ concentration was seen. It is inferred that due to the removal of CO by the oxidation reaction a consequent reduction in H₂ concentration by the reverse water gas shift reaction occurred.⁴

4. Conclusions

In this study, catalytic steam gasification of bio-char derived from the pyrolysis of sugar cane bagasse was performed. It has been suggested that high temperature steam gasification of char is recommended for the production of hydrogen. In this study we have investigated the feasibility of the process of gasification of bagasse bio-char, in relation to a range of process conditions, including gasification temperatures to over 1000 °C, a range of steam flow rates and the influence of three different catalysts, Ni-dolomite, Ni-MgO and Ni-Al₂O₃, on the catalytic gasification of the bio-char. The following conclusions can be made:

It was found that the highest H₂ yield of 187.25 mmol. g⁻¹ of char was obtained using the Ni-Al₂O₃ catalyst. As compared to no catalyst, the H₂ concentration in the product gas was increased from 57.74 to 76.81 vol.%. This higher H₂ yield with Ni-Al₂O₃ catalyst was attributed to the larger surface area of this catalyst.

The influence of gasification temperature on H₂ yield revealed that the most suitable temperature to obtain the highest H₂ yield was found to be 950 °C. Increase in gasification temperature from 750 to 950 °C favoured endothermic reactions causing significant increase in H₂ yield from 45.30 at 750 °C to 187.25 mmol. g⁻¹ of char at 950 °C.

The influence of steam flow rate on H₂ yield found that initially with the increase in steam flow rate from 6 to 15 ml h⁻¹ the H₂ yield was increased from 187.25 to 208.41 mmol. g⁻¹ of biomass char. However further increase in steam flow rate resulted in a decrease in H₂ yield to 168.58 mmol. g⁻¹ for 20 ml h⁻¹ and to 174.20 mmol. g⁻¹ for 25 ml h⁻¹.

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Table 1. Proximate and ultimate analysis of sugar cane bagasse.

Proximate Analysis (as received)				
Feed stock	Volatile matter (wt.%)	Fixed carbon (wt.%)	Moisture (wt.%)	Ash (wt.%)
Bagasse	81.55	10.91	5.92	1.62
Ultimate analysis (ash-free basis)				
Feed stock	C (wt.%)	H (wt.%)	N (wt.%)	O ^a (wt.%)
Bagasse	46.25	5.72	0.81	47.21

^a Calculated by difference

Table 2. Ultimate analysis of the sugar cane bagasse char and metals analysis of bio-char ash.

	Sugar cane Bagasse Bio-char (wt.%)
Elemental Analysis (Ash-free basis)	
C	81.55
H	1.85
N	0.96
O	15.63
Ash Analysis	
Al ₂ O ₃	9.1
BaO	0.1
CaO	9.4
Fe ₂ O ₃	3.4
K ₂ O	5.2
MgO	3.1
MnO	0.6
P ₂ O ₅	1.7
SiO ₂	47.8
SrO	0.2
TiO ₂	0.7

Table 3. Surface properties of the fresh catalysts

Fresh Catalyst	BET surface area	BJH pore volume	Average pore size
	$\text{m}^2 \text{g}^{-1}$	$\text{cm}^3 \text{g}^{-1}$	nm
10 wt.% Ni-dolomite	5.56	0.0308	3.78
10 wt.% Ni- Al_2O_3	76.82	0.2792	5.64
10 wt.% Ni-MgO	53.90	0.3939	36.08

Table 4. Gasification of sugar cane bagasse char at 950 °C using various catalysts

	Catalyst			
	no catalyst	10 wt.% Ni-Dolomite	10 wt.% Ni-Al ₂ O ₃	10 wt.% Ni-MgO
H ₂ (mmol. g ⁻¹ of biomass)	25.24	28.09	46.81	44.69
H ₂ (mmol. g ⁻¹ of char)	100.97	112.36	187.25	178.75
H ₂ /CO	2.31	2.29	5.00	3.58
CO/CO ₂	1.47	2.04	2.00	4.29
H ₂ /CO ₂	3.39	4.68	10.01	15.38
H ₂ /CH ₄	374.97	486.93	455.77	511.95
CH ₄ /CO	0.01	0.00	0.01	0.01
CH ₄ /CO ₂	0.01	0.01	0.02	0.03
Mass balance (wt.%)				
Gas/(char + steam injected)	23.83	21.84	11.8	12.77
Gas/(char)	274.74	265.88	225.53	237.82
Mass balance	95.26	92.95	96.11	94.83

Table 5. The influence of temperature on gasification of bagasse char using 10 wt.% Ni-Al₂O₃ catalyst

	Temperature (°C)			
	750	850	950	1050
H ₂ (mmol. g ⁻¹ of biomass)	11.33	30.21	46.81	42.86
H ₂ (mmol. g ⁻¹ of char)	45.3	120.84	187.25	171.44
H ₂ /CO	8.30	4.19	5.00	4.06
CO/CO ₂	0.34	0.71	2.00	1.58
H ₂ /CO ₂	2.86	2.99	10.01	6.42
H ₂ /CH ₄	185.96	115.81	455.77	2910.74
CH ₄ /CO	0.04	0.04	0.01	0.00
CH ₄ /CO ₂	0.02	0.03	0.02	0.00
Mass balance (wt.%)				
Gas/(char + steam injected)	5.05	14.72	11.8	17.19
Gas/(char)	94.59	293.5	225.53	288.4
Mass balance	96.40	95.86	96.11	99.07

Table 6. The influence of steam flow rate on gasification of bagasse char using 10 wt.% Ni-Al₂O₃ catalyst

	Steam flow rate (ml h ⁻¹)			
	6	15	20	25
H ₂ (mmol. g ⁻¹ of biomass)	46.81	52.1	42.15	43.55
H ₂ (mmol. g ⁻¹ of char)	187.25	208.41	168.58	174.2
H ₂ /CO	5.00	4.98	4.80	4.51
CO/CO ₂	2.00	1.51	0.90	1.06
H ₂ /CO ₂	10.01	7.51	4.31	4.80
H ₂ /CH ₄	455.77	336.55	271.68	231.99
CH ₄ /CO	0.01	0.01	0.02	0.02
CH ₄ /CO ₂	0.02	0.02	0.02	0.02
Mass balance (wt.%)				
Gas/(char + steam injected)	11.8	6.18	5.34	4.61
Gas/(char)	225.53	292.55	316.23	326.05
Mass balance	96.11	91.39	97.57	97.14

FIGURE CAPTIONS

Fig. 1. Schematic diagram of the fixed-bed high temperature reactor

Fig. 2. Scanning electron micrographs of fresh and reacted catalysts (a) fresh 10 wt.% Ni-dolomite, (b) fresh 10 wt.% Ni-Al₂O₃, (c) fresh 10 wt.% Ni-MgO.

Fig. 3. Composition of gases in the product mixture from gasification of sugar cane bagasse char using different catalysts

Fig. 4. The influence of temperature on gas composition during steam gasification of sugar cane bagasse char

Fig. 5. The influence of steam flow rate on gas composition during gasification of sugar cane bagasse char

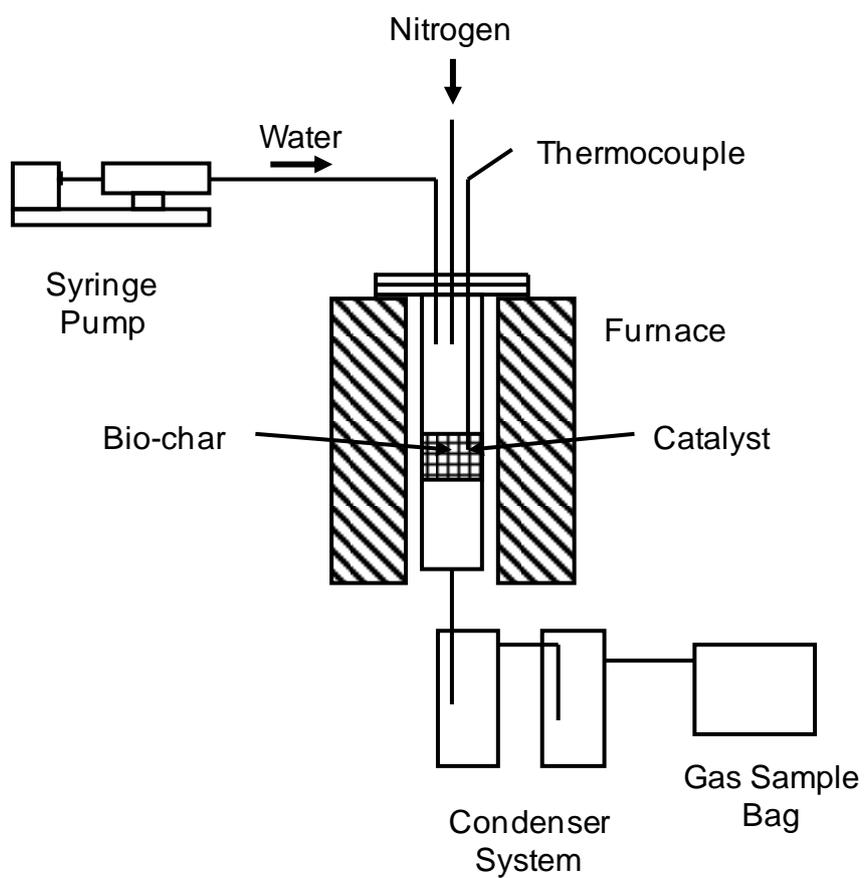


Fig. 1. Schematic diagram of the fixed-bed high temperature reactor

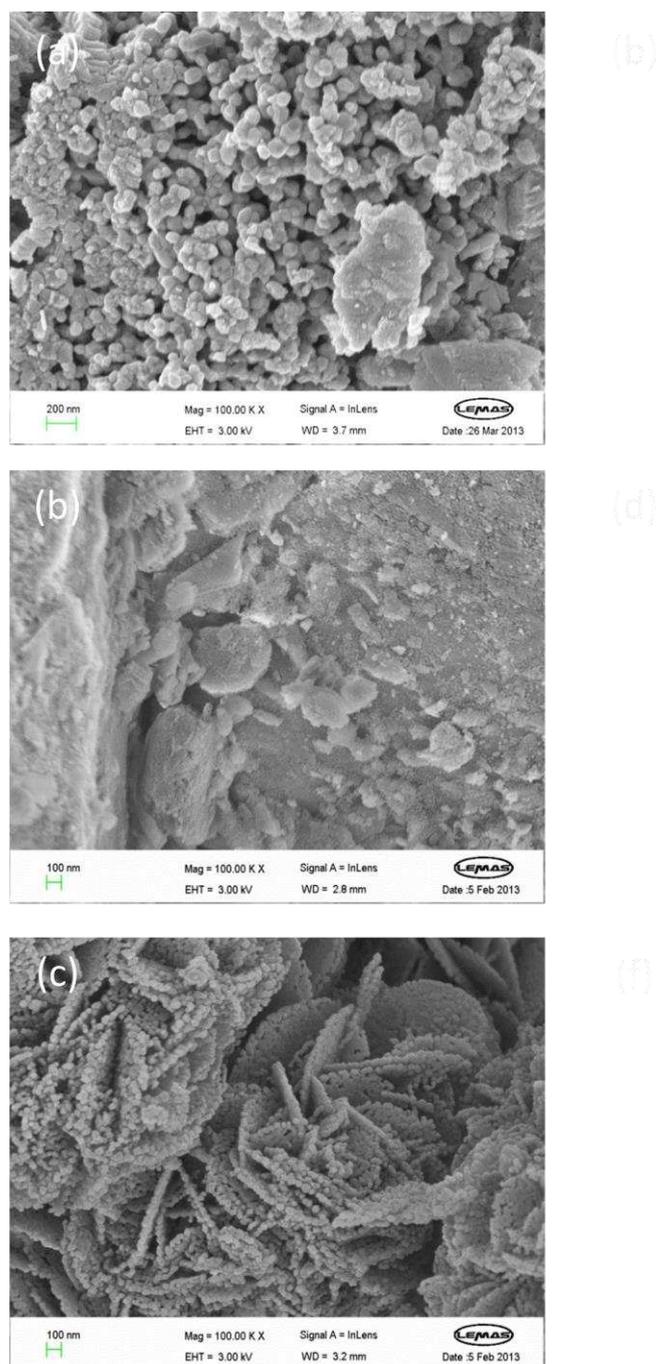


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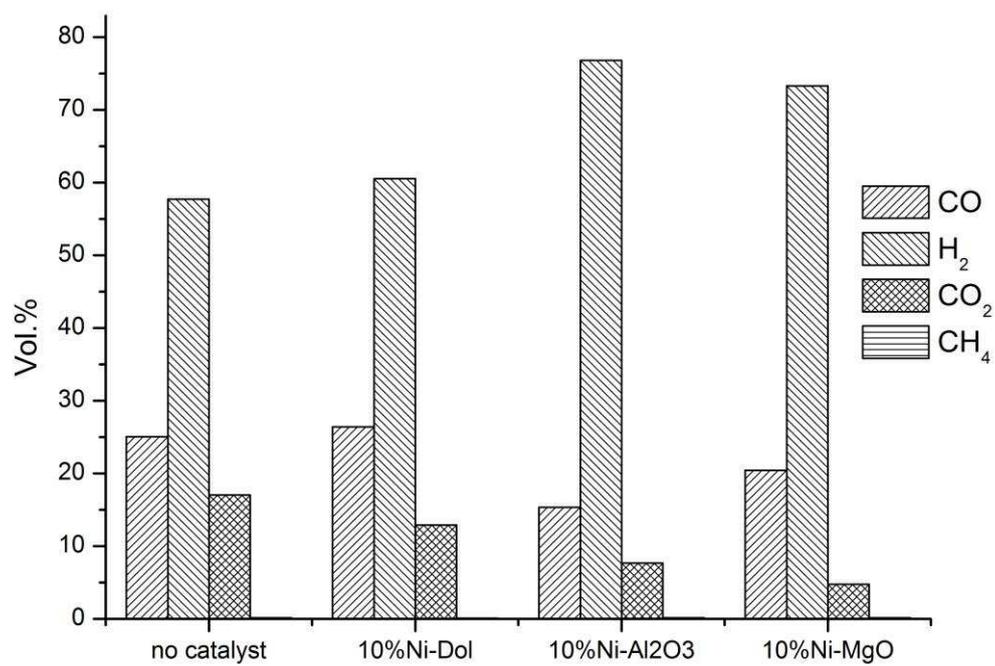


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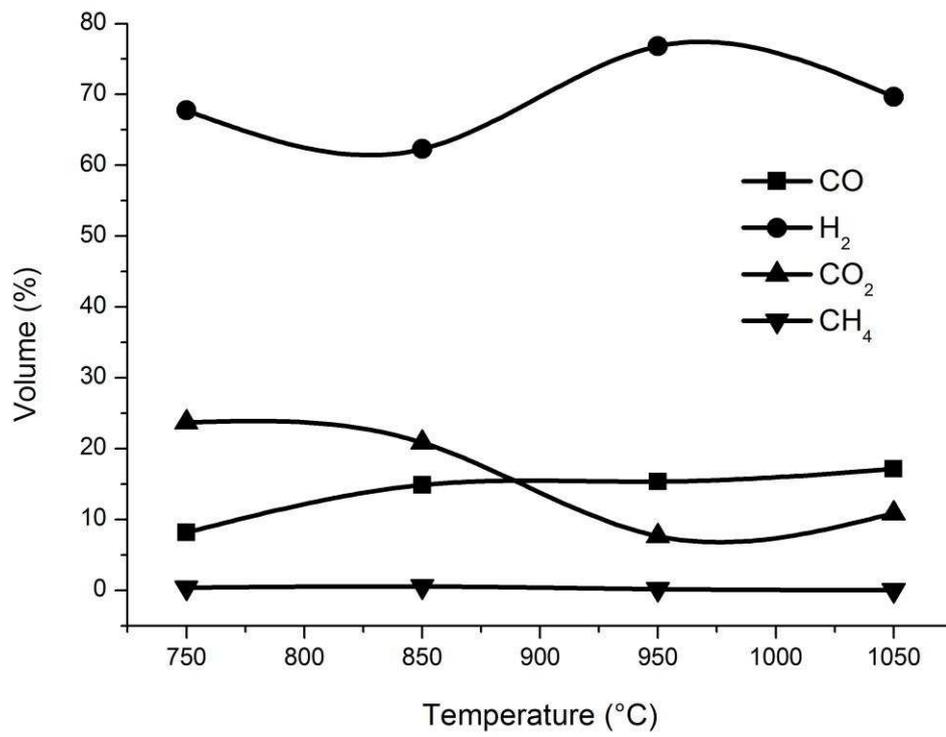


Fig. 4. The influence of temperature on gas composition during steam gasification of sugar cane bagasse char

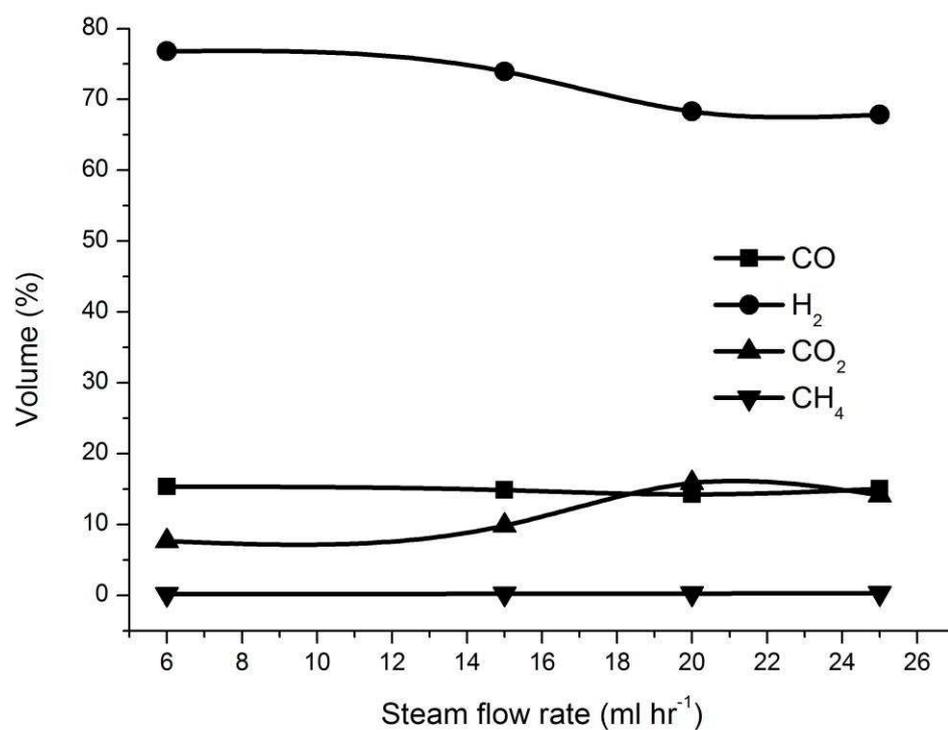


Fig. 5. The influence of steam flow rate on gas composition during gasification of sugar cane bagasse char