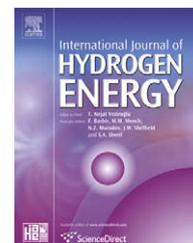


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Hydrogen-rich gas production from biomass steam gasification in an updraft fixed-bed gasifier combined with a porous ceramic reformer

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ABSTRACT

This paper investigates the hydrogen-rich gas produced from biomass employing an updraft gasifier with a continuous biomass feeder. A porous ceramic reformer was combined with the gasifier for producer gas reforming. The effects of gasifier temperature, equivalence ratio (ER), steam to biomass ratio (S/B), and porous ceramic reforming on the gas characteristic parameters (composition, density, yield, low heating value, and residence time, etc.) were investigated. The results show that hydrogen-rich syngas with a high calorific value was produced, in the range of 8.10–13.40 MJ/Nm³, and the hydrogen yield was in the range of 45.05–135.40 g H₂/kg biomass. A higher temperature favors the hydrogen production. With the increasing gasifier temperature varying from 800 to 950 °C, the hydrogen yield increased from 74.84 to 135.4 g H₂/kg biomass. The low heating values first increased and then decreased with the increased ER from 0 to 0.3. A steam/biomass ratio of 2.05 was found as the optimum in the all steam gasification runs. The effect of porous ceramic reforming showed the water-soluble tar produced in the porous ceramic reforming, the conversion ratio of total organic carbon (TOC) contents is between 22.61% and 50.23%, and the hydrogen concentration obviously higher than that without porous ceramic reforming.

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1. Introduction

In the past decades, renewable biomass resources such as short-rotation woody crops, herbaceous biomass, and agricultural residues have received increasing attention as an interesting renewable energy source [1]. As a source of renewable energy, biomass energy has significant environmental benefits including lower emissions of carbon dioxide

and other greenhouse gases. One of the attractive ways to utilize biomass energy is hydrogen production. Hydrogen has good properties as a fuel for internal combustion engines in automobiles. It is used as a clean power source for fuel cells. Also, its use could be advantageous as a clean energy carrier for heat supply and transportation purposes [2].

Biomass gasification process has emerged as a clean and efficient way of producing hydrogen. It is a well-known

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technology that can be classified depending on the gasifying agent: air, steam, steam–oxygen, air–steam, oxygen-enriched air, etc. [3]. Several biomass gasification reactor designs have been developed and evaluated and can be generally classified into three categories, they are fixed bed [4], fluidized bed [5] and moveable bed [6]. These gasifiers are conducted widely by many researchers in biomass gasification [7].

Several advantages of steam as gasification agent are: producing a gaseous fuel with relatively higher H₂ content, eliminating the need for an expensive oxygen plant when oxygen is employed as gasification agent, reducing the diluting effect of N₂ from air and producing higher heating value syngas [8]. Much has been published in the literature on experimental investigations into the biomass steam gasification processes. Turn et al. [9] investigated hydrogen production from biomass gasification using a bench scale fluidized bed gasifier. Lv et al. [3] discussed biomass air–steam gasification in a fluidized bed. Different effects such as temperature, steam to biomass ratio (S/B), equivalence ratio (ER) and biomass particle size were investigated. Chaudhari et al. [10] studied hydrogen production via steam gasification of two biomass derived chars in a fixed bed. Higher concentration hydrogen was produced by the simple steam gasification process. Two distinct strategies converting thermochemically biomass to hydrogen are gasification followed by shift conversion and catalytic steam reforming of the whole oil or its fraction [11]. Many researchers carried out biomass gasification and catalytic reforming on different reactor. Rapagn et al. [12] investigated catalytic biomass steam gasification in a bench scale plant consisting of a fluidized bed gasifier and a secondary catalytic fixed-bed reactor. Kimura et al. [13] discussed the different catalytic performance of Ni/CeO₂/Al₂O₃ catalysts in steam gasification of biomass. A Ni/olivine catalyst was tested by Świerczyński et al. [14] in a fixed-bed reactor in toluene steam reforming as a tar destruction model reaction for a fluid bed biomass steam gasification. Recently, Tomishige et al. [15,16] have investigated the gasification of biomass with steam using different catalysts (Rh/CeO₂/SiO₂, Ni/CeO₂/Al₂O₃) in fluid bed reactor. And they found that these catalysts showed effectiveness in the steam or air gasification and reforming of biomass, and high resistance to coke deposition and high stability was showed in the reforming process.

Although many researchers had experimentally studied hydrogen production by biomass gasification and the reforming of product gas and tars, these gasification studies were conducted on batch-type reactor, fluidized bed gasifier or bubbling fluidized bed, and most reforming processes were carried out with catalyst. Only a few studies explore hydrogen-rich gas production from continuous biomass steam gasification in an updraft gasifier and the product gases and tars reforming with porous ceramic. In this work, continuous biomass feed for updraft fixed-bed steam gasifier was investigated, a novel method of a porous ceramic reformer combined with gasifier was proposed to reform gases and crack tars produced in biomass steam gasification, in which a porous ceramic rather than catalyst as filling material in the secondary reformer was employed, and the properties of regenerative heat and trapping for tars and soot carbon were utilized for tar and gas reforming.

2. Experimental

The original material (pine sawdust) used as the feedstock for gasification was obtained from a timber mill in Dalian City, China. The particle size of this pine feedstock is between 0.2 and 0.4 mm. The results of proximate analysis and ultimate analysis of biomass sample used for the experiment are shown in Table 1. The carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) analyses of pine sawdust were performed on a CHNS/O analyzer (Elementar, VarioEL III), and the ash content obtained by carrying the samples at oxygen (O) was calculated by difference to 100%. The proximate analysis of the samples was carried out according to standard norms. The moisture, ashes and volatile matter were measured according to the ASTM standard test method no. E871, D1102 and E872. The fixed carbon was calculated by difference to 100%. The higher heating value (HHV) was measured with oxygen bomb calorimeter.

The experimental apparatus setup that was used to perform steam gasification experiments is shown in Fig. 1. It consists of a fixed-bed gasifier with a continuous biomass feeding system, a steam reformer with porous ceramic packing layer, a steam/gas feeding line, a cooling system for the separation of water and tar, and various measurement/analysis devices.

The gasifier and reformer are two same stainless steel cylindrical tubes (1500.0 mm long and 87.5 mm i.d.), they were placed inside two same externally electrical furnaces (3.3 kW, 220 V, 15 A) which provided the heat for reaction and steam reform. The internal configuration of reformer fixed-bed reactor is as same as gasifier; in particular, a porous ceramic layer (200 mm in length and 87 mm in diameter) was located in the middle of the reformer. Table 2 shows the chemical composition and physical properties of porous ceramic filled in the reformer. Two porous ceramics with same physical structure were employed in the reformer and each was 100 mm in length and 87 mm in diameter. Two K-type thermocouples with a diameter of 0.3 mm were mounted through the wall of the reactor and measured the temperatures at the reactor centerline. Oxygen and steam were employed as gasification agents for the tests. The steam of 120 °C was generated in an electrical heated boiler, and the steam flow rate was controlled with a voltage regulator which controlled the voltage of boiler. All experiments were carried out at atmospheric pressure.

The original feed was fed under gravity to the top of the gasifier by a continuous feeding system composed of a screw

Table 1 – proximate analysis and ultimate analysis of pine sawdust

Proximate analysis (wt.%)	Ultimate analysis (wt.% daf)		
Moisture content	3.93	C	44.75
Fixed carbon	18.88	H	6.31
Volatile	76.85	O (difference)	47.21
Ash	0.34	N	1.68
		S	0.05
Higher heating value (MJ/kg, db)	18.47		

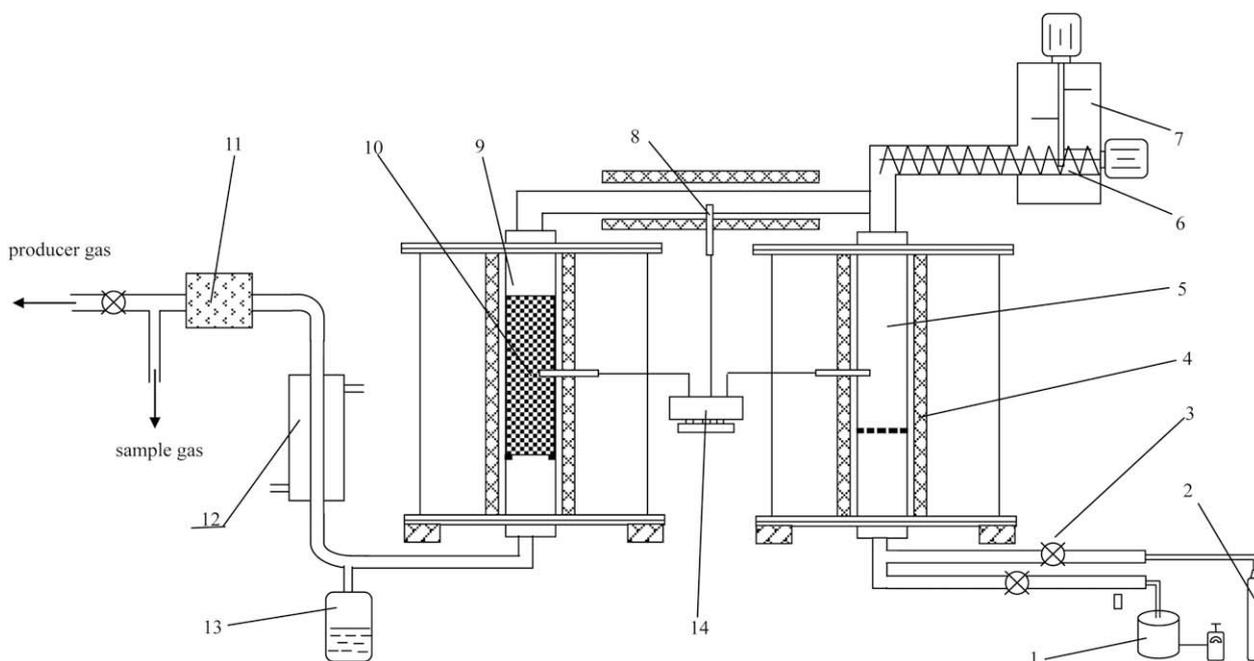


Fig. 1 – Diagram of the fixed-bed biomass gasification system: (1) steam boiler; (2) oxygen tanker; (3) valve; (4) electric furnaces; (5) fixed-bed gasifier; (6) screw feeder; (7) biomass hopper; (8) thermocouple; (9) secondary reformer; (10) porous ceramic layer; (11) purification and drying device; (12) condenser; (13) tar collector; (14) PID temperature controller.

feeder and a variable speed motor. The gasifier and the reformer were preheated to the desired temperature using the external electrical furnaces by passing air flowing. When the desired temperature was reached, the airflow was turned off and switched to the desired gas (steam or oxygen) at the desired flow rate. As the reactor temperature was stabilized, the feeder was turned on at the desired rotate speed and the test begun. Generally, after the commencement of the feeding, it took about 20 min to obtain a steady state. For each run, three samples were taken in the stable state at an interval of 5 min. To verify the validity of data, all experiments were performed two times.

Products (gas and liquids) exiting the gasifier passed a stainless steel cylindrical tube (500.0 mm long and 30 mm i.d.) for preventing the product gas temperature decrease, and then the products were introduced into secondary reformer for tar reforming. After left the reformer, the gasification products passed through a heat exchange system. The volume of dry gas produced was measured by means of a volumetric gas-meter.

To clean the gas and separate it from the condensable fraction, two stages of traps were setup. First, the gases leaving the secondary reformer made direct contact with a countercurrent water-cooled heat exchanger, and the tar condensed from producer gas was collected in a vial. Second, the producer gas pass through a tube filled with CaCl_2 for the sake of steam removal and gas purity. Gases were collected using a gasbag only after 10 min of gasification.

The product gas was collected periodically through a gas syringe and analyzed off-line by gas chromatography (GC). The gas fraction composition, mainly H_2 , CO , CH_4 , CO_2 , C_2H_4 , and C_2H_6 , was identified using a gas chromatograph with

a thermal conductivity detector and a double injector connected to three 5 m length, 3 mm diameter columns with helium as carrier gas. The first column was 5A 100:120 chromatographic column for giving H_2 , O_2 , N_2 , CO , CH_4 concentrations; the second column is TDX-01 yielded CO_2 concentration, the third column is GDX-102 chromatographic column as it was used for C_2H_4 , C_2H_6 and some light hydrocarbons detection. The contents of total carbon (TC), total organic carbon (TOC) and inorganic carbon (IC) in water-soluble tars were carried out using a TOC analyzer (Shimadzu 5050 TOC- V_{CPH} , Japan).

3. Results and discussion

The effect of reaction temperature, equivalence ratio, steam to biomass ratio and porous ceramic was studied. In the present study, all the temperatures of reformer were set as same as the temperatures of gasifier. As a comparison, the effect of reforming without porous ceramic was investigated in the same operating condition of varying steam to biomass ratio.

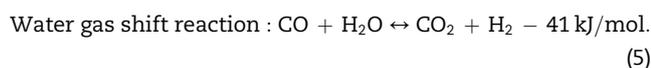
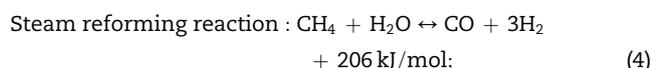
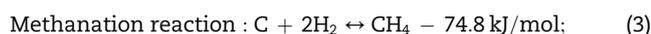
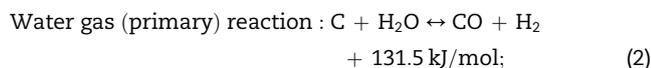
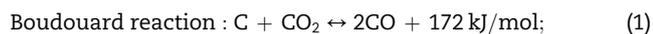
3.1. Effect of reaction temperature

The effect of reaction temperature on biomass steam gasification is investigated. Reactions were performed at four reaction temperatures from 800 to 950 °C in 50 °C increments. The operating conditions and test results are presented in Table 3 and Fig. 2. It can be observed from Fig. 2 that hydrogen concentration increased from 39 to 55% with the temperature. Moreover, an increasing trend of H_2 was shown with the increasing reactor temperature. Carbon monoxide has

Table 2 – The chemical composition and physical properties of porous ceramic

Chemical composition (wt.%)		Physical properties	
SiO ₂	26	Density (kg/m ³)	2100
Al ₂ O ₃	60	Specific heat (kJ/(kg K))	850–1050
MgO	11	Softening temperature (°C)	1600
Fe ₂ O ₃	1	Heat conduction coefficient (20–1000 °C, W/(mK))	1.4–2
Na ₂ O + K ₂ O + CaO	1.1–1.5	Thickness of Wall (mm)	0.45
TiO ₂ + BaO	0.8	Porosity (%)	80
		Surface Area (m ² /m ³)	805

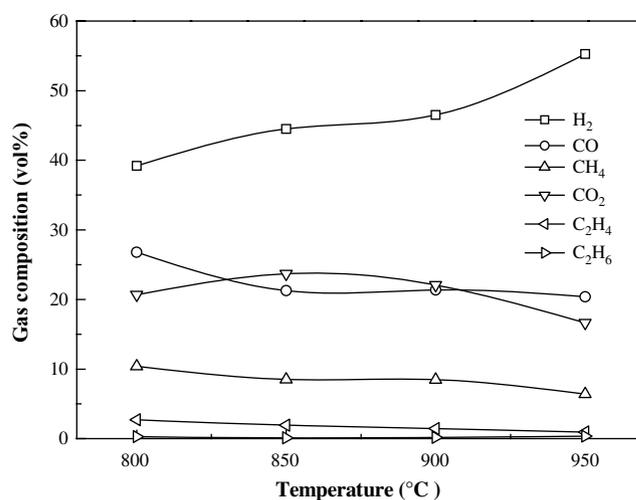
a smaller decrease from 27 to 20% between 800 and 950 °C. Methane and carbon dioxide decreased from 10 to 6% and from 21 to 17%, respectively. As the steam gasification incorporated a series of complex reactions, which is presented as follows, the results of gas composition varied with the operating conditions.



Higher temperature favors the products in reactions (1), (2) and (4) (endothermic reactions), and the reactants in reactions (3) and (5) (exothermic ones). Therefore, endothermic reactions were strengthened with a higher reaction temperature, and caused an increment of H₂. To enhance H₂ yield, a balance should be established between the maximum H₂ yields and

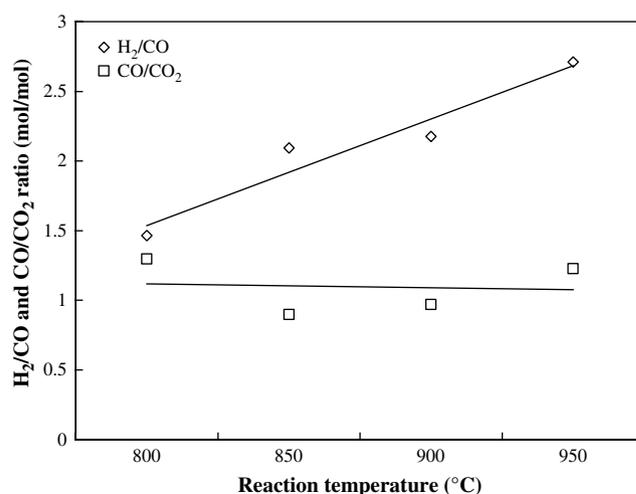
Table 3 – Experimental results of different reaction temperature

Reactor and reformer temperature	800	850	900	950
Wet feed rate (kg/h)	0.48	0.48	0.48	0.48
Dry feed rate (kg/h)	0.44	0.44	0.44	0.44
Steam rate (kg/h)	0.67	0.67	0.67	0.67
Steam to biomass ratio	1.4	1.4	1.4	1.4
Gas density (kg/Nm ³)	0.68	0.63	0.61	0.53
Gas yield (m ³ /kg daf biomass)	2.14	2.51	2.47	2.74
Low heating value (MJ/Nm ³)	12.25	10.10	11.51	10.02
Residence time (s) at reactor temperature	7.11	4.67	4.15	3.25
Hydrogen yield (g H ₂ /kg biomass, dry basis)	74.84	99.55	102.77	135.40

**Fig. 2 – Effect of reaction temperature on gas composition.**

the conversion of char to gas through the selection of a suitable reaction temperature.

Fig. 3 shows the molar ratios of H₂/CO and CO/CO₂ in the production gas. The molar ratio of H₂/CO increases with an increase reaction temperature, while the CO/CO₂ molar ratio decreases slightly. The molar ratio of H₂/CO between the values of 1 and 2 (1 < H₂/CO < 2) should be useful for the chemical industry to synthesise products such as methanol and virgin naphtha [17]. In this study, the molar ratio of H₂/CO is between 1.5 and 2.7 (1.5 < H₂/CO < 2.7). The H₂ may be formed in three paths: the first one is derived from the fast pyrolysis at the commencement of biomass introduced into reactor, the second is produced through the endothermic char reactions [8], the third one is produced through the further cracking reaction of heavier hydrocarbons and tars trapped by the porous ceramic. The higher molar ratio of CO/CO₂ strongly influences the calorific content of the producer gas. With reaction temperature increase, the molar ratio varies between 0.9 and 1.3 (0.9 < CO/CO₂ < 1.3), and the LHV of production gas shows a decreasing trend (as showed in Table 3).

**Fig. 3 – Effect of reaction temperature on H₂/CO and CO/CO₂ molar ratio.**

3.2. Effect of equivalence ratio

The equivalence ratio (ER) is a crucial parameter in the biomass steam gasification when the oxygen or air was employed in the processes. The equivalence ratio is defined as the amount of air added relative to the amount of air required for stoichiometric combustion. Since the presence of nitrogen dilutes the produce gas and decrease the gas quantity, oxygen was employed as gasification agents. Based on the ultimate analysis of pine sawdust, the stoichiometric pure oxygen demand was calculated as 3.21 Nm³ oxygen/kg dry pine sawdust.

Table 4 and Fig. 4 show the operating condition and test results with varying ER. The equivalence ratio was increased from 0 to 0.30 at a constant feed rate. As shown in Fig. 4, hydrogen concentration decreased from 44.45 to 23.56% with the varying ER. On the contrary, the concentration of carbon dioxide increased sharply from 23.70 to 48.74% with the increasing ER. Carbon monoxide first increased and then decreased. The increased ER influences the gas composition from two sides. One is higher ER supplies more oxygen, as a result, the temperature of reaction zone increased and the reaction of gasification is strengthened. The other is higher ER bring on the low heating value of producer gas decline due to more H₂ and CO is consumed.

Fig. 5 shows the change of H₂/CO and CO/CO₂ molar ratios in the product gas with the equivalence ratio. It is indicated that the yield of H₂ became more less. The molar ratio of H₂/CO decreases from 2.1 to 1.2, while the ratio of CO/CO₂ changes between 1.1 and 0.4. It can be inferred that, when oxygen was not introduced into reactor and only steam as the gasification media (ER = 0), the reactions (2) and (5) would be the primary reactions in the gasification process, however, as ER increased, more oxygen was supplied to the system, reactions (6)–(8) participate in the gasification process. In Table 4, the LHV first increased and then decreased with the increased ER from 0 to 0.3.

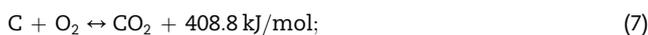
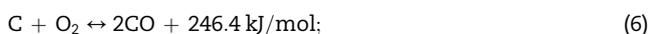


Table 4 – Experimental results of different equivalence ratio

Equivalence ratio	0	0.05	0.1	0.3
Reactor temperature (°C)	850	850	850	850
Wet feed rate (kg/h)	0.48	0.48	0.48	0.48
Dry feed rate (kg/h)	0.44	0.44	0.44	0.44
Steam rate (kg/h)	0.67	0.67	0.67	0.67
Steam to biomass ratio	1.4	1.4	1.4	1.4
Gas density (kg/Nm ³)	0.63	0.68	0.75	0.83
Gas yield (m ³ /kg daf biomass)	2.51	2.24	2.07	1.89
Low heating value (MJ/Nm ³)	10.10	12.67	11.44	8.10
Residence time (s) at reactor temperature	4.67	6.93	5.05	3.62
Hydrogen yield (g H ₂ /kg biomass, dry basis)	99.55	79.07	64.02	45.05

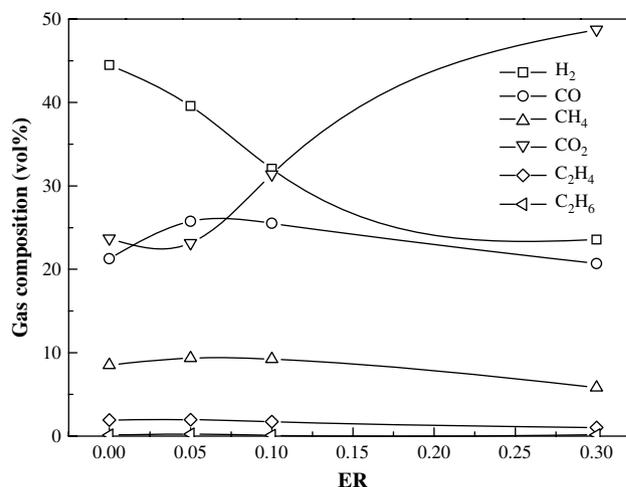


Fig. 4 – Effect of equivalence ratio on gas composition.



As more oxygen was fed, less H₂ and other combustible gases through oxidization reaction. Although these exothermic oxidation reactions lead to release more heat to the gasification process, and optimize quality of product gases to some extent [17], as more CO₂ and less combustible gases production which result in the LHV decrease. So, a suitable ratio would be existed in the gasification process. An optimum value of ER was found to be 0.05 in this study. Gas yield declined from 2.51 to 1.89 m³/kg daf biomass with increasing ER. Hydrogen yield also declined from 99.55 to 45.05 g H₂/kg biomass with ER.

3.3. Effect of steam/biomass ratio

The steam/biomass ratio (S/B) has been studied at 1.05, 2.05, 2.53 and 3.47 at the temperature 850 °C. The varying steam/

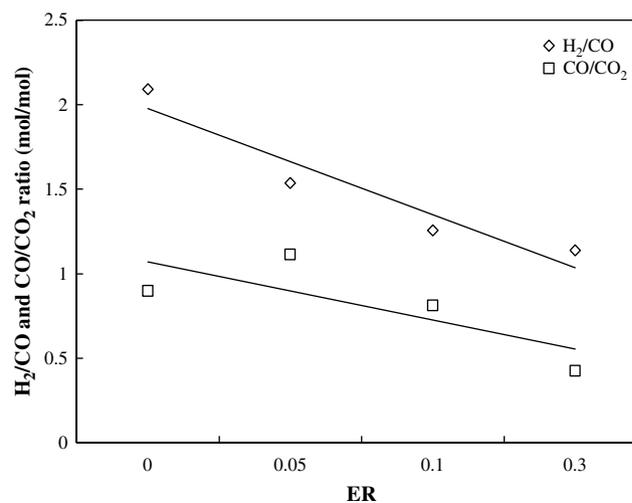


Fig. 5 – Effect of equivalence ratio on H₂/CO and CO/CO₂ molar ratio.

Table 5 – Experimental results of different steam/biomass ratio

Steam to biomass ratio	1.05	2.05	2.53	3.47
Reactor temperature (°C)	850	850	850	850
Wet feed rate (kg/h)	0.48	0.48	0.48	0.48
Dry feed rate (kg/h)	0.44	0.44	0.44	0.44
Steam rate (kg/h)	0.50	0.98	1.21	1.66
Gas density (kg/Nm ³)	0.59	0.56	0.54	0.47
Gas yield (m ³ /kg daf biomass)	1.83	1.99	1.77	1.77
Low heating value (MJ/Nm ³)	11.36	11.33	12.22	11.94
Residence time (s) at reactor temperature	7.72	5.12	4.64	3.67
Hydrogen yield (g H ₂ /kg biomass, dry basis)	77.99	89.80	83.34	95.89

biomass ratio was controlled by keeping the biomass feed rate while changing steam rate. Oxygen was not introduced in gasifier. The operating conditions and test results are shown in Table 5 and Fig. 6.

It can be seen that the gas composition displayed increasing trend with the S/B increasing from 47.61 to 60.59%, carbon monoxide levels has a slight change in the range of S/B from 1.05 to 3.47, while carbon dioxide decreased from 26.71 to 14.47%. As water gas (primary) reaction (2) and water gas shift reaction (5) take a key role in the steam gasification process, hydrogen production was raised. Although some researchers [9,18] reported different phenomena with our results, that is, with the increase of the S/B, H₂ and CO₂ contents increased while CO concentration dropped, different biomass species, the type and structure of reactor and reformer, operating conditions and gasification agents lead to different results. In our study, the porous ceramic reformer for tars in the product gas reforming may take a distinct effect in the gasification process. The difference of gasifier with and without porous ceramic reformer was studied in the next section in detail. The concentration of methane and other hydrocarbons (C₂H₄, C₂H₆) holds a relative smooth varying with S/B. The gas yield exhibited a trend of first increase and then decrease. As the increasing S/B, more steam was introduced into reactor, which led to the decrease of gas residence time (s) in reactor.

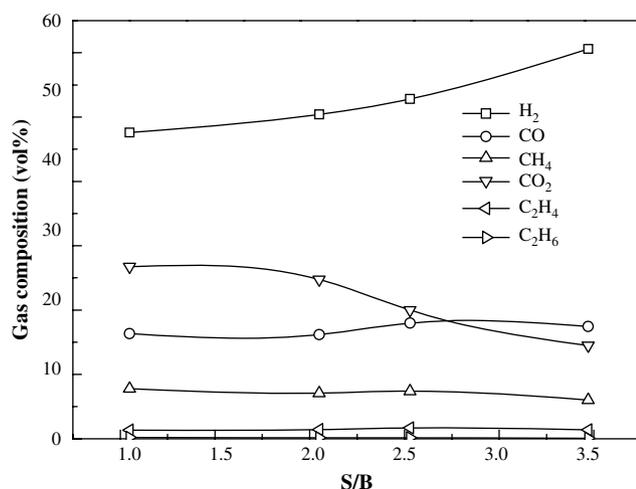
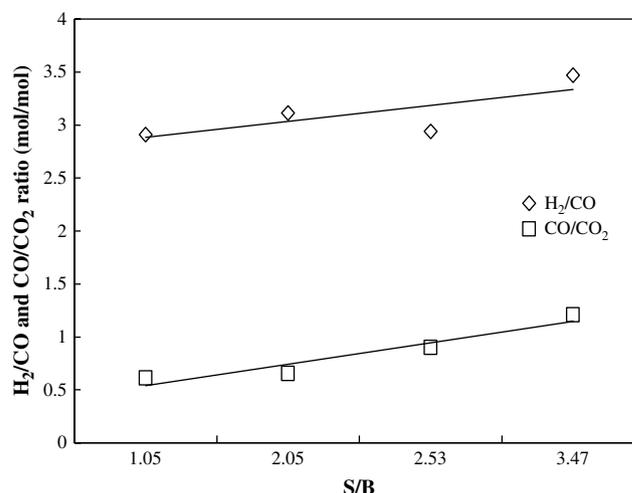
**Fig. 6 – Effect of steam to biomass ratio on gas composition.****Fig. 7 – Effect of steam to biomass ratio on H₂/CO and CO/CO₂ molar ratio.**

Fig. 7 shows the molar ratio of H₂/CO and CO/CO₂ in product gas. As the steam increases, H₂ and CO generation increases and CO₂ decreases. The molar ratio of H₂/CO increases with the steam/biomass ratio increase. The H₂/CO and CO/CO₂ molar ratio changes slightly between 2.91 and 3.47 and between 0.61 and 1.20, respectively. It can be inferred that the water–gas shift reaction favors H₂ production, and porous ceramic may be promote water–gas reaction and tar and heavier hydrocarbon cracking when the products pass through the pore embedded in ceramic.

Although, on the basis of experiments, higher S/B produce larger amount of hydrogen yield, as a byproduct, higher water content was produced in the gasification processes. As we know, the separation steam from producer gas easily by condensation and dryness, however, more energy was consumed to produce excess steam as well as consumed in the process of condensation [19]. So, it may be necessary to select an optimal steam/biomass ratio according to different operating condition. In this study, the optimal value of S/B was found to be 2.05 under the operating condition shown in Table 5.

3.4. Effect of porous ceramic reforming

Tar production in biomass gasification is a very important problem for the reason of blocking pipeline of gasifier and polluting environment. As the filling material, porous ceramic was filled in the secondary reformer for tar cracking. When producer gas passed through porous ceramic layer, tar presence in producer gas was introduced simultaneously into the reformer, and was decomposed into small molecule such as H₂, CO, CO₂, etc. In this process, due to plenty of through pores embedded in the porous ceramic, steam reforming reaction (4) and water gas shift reaction (5) could be improved for the products sufficient contact.

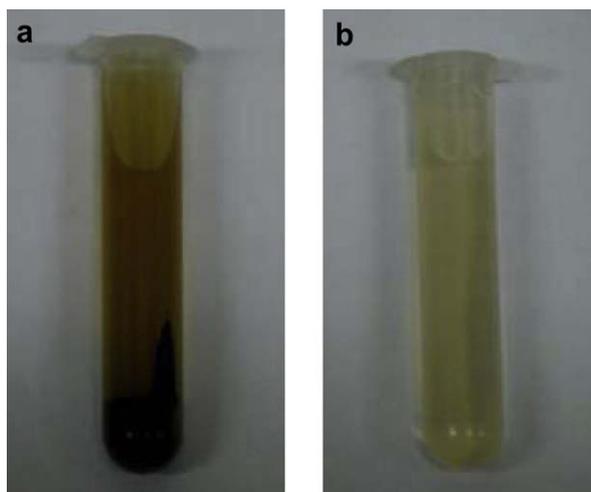
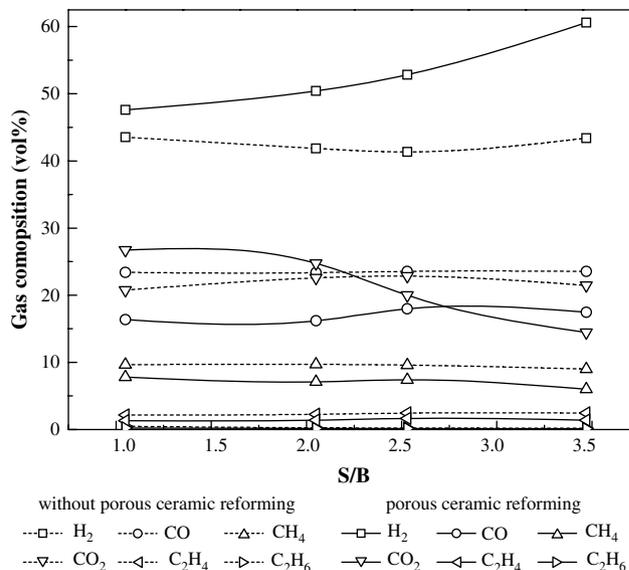
Table 6 shows the content of TC (total carbon), TOC (total organic carbon) and IC (inorganic carbon) in the water-soluble tars in the process of reforming with or without porous ceramic. Since the tar in organic phase is too little to be

Table 6 – The comparison of TOC in tars produced from two types of reforming

Steam/biomass ratio		1.05	2.05	2.53	3.47
Without porous ceramic reforming	TC (mg/l)	899.13	806.50	789.39	755.50
	TOC (mg/l)	766.88	699.38	694.37	692.25
	IC (mg/l)	132.25	107.19	95.01	63.21
With porous ceramic reforming	TC (mg/l)	511.96	558.13	599.00	399.13
	TOC (mg/l)	440.13	489.38	537.38	344.50
	IC (mg/l)	58.71	68.66	61.59	54.67
TOC conversion (%)		33.24	20.20	13.74	42.34

measured, only the dissolved tars in the water phase were detected when using porous ceramic reforming. The content of TOC in tars varies in the range of 693.25–766.88 mg/l without ceramic reforming, while change between 344.50 and 537.38 mg/l with ceramic reformer. The conversion of TOC is roughly between 22.61 and 50.23% in the two types of reforming process. Fig. 8 shows the appearance comparison of two types of tars produced from porous ceramic reforming and without porous ceramic reforming. It can be seen that, for porous ceramic reforming, it is hardly found the heavy tars in the organic phase, and the main composition is the water-soluble tars, while the mixing of organic phase tars and the dissolved tars in the water phase was observed for without porous ceramic reforming. This may be explained as follows: the porous ceramic in the reformer promoted reaction (9) when the steam and gasification gas entered the pores embedded in porous ceramic. And then, the heavy oil vapours, C₁–C₅ hydrocarbons, naphthalin, gas oils and aromatic compounds were decomposed to yield a mixture of small mole gases (H₂, CO, CO₂, etc.).

Steam porous ceramic reforming of tars → H₂ + CO + CO₂
+ hydrocarbon + ..., ΔH > 0

**Fig. 8 – The appearance comparison of tars produced from two types of reforming: (a) without porous ceramic reforming; (b) porous ceramic reforming.****Fig. 9 – Effect of porous ceramic filter on gas composition.**

In addition, the presence of inorganic compositions of porous ceramic, for example MgO [20], Fe₂O₃ [21], Na₂O [22], K₂O [23], CaO [24], TiO₂ [25] and BaO [26], etc. may take some catalyst or support roles in the tars and heavy substances cracking, the water gas shift reaction (4) and steam reforming reaction (5), which may enhance H₂ production. The steam introduced into the gasifier may have some improved function in the process of char conversion gas. Due to the larger contact area and the good regenerative heat of porous ceramic, the reforming reaction may be promoted. Therefore, the production of H₂ with porous ceramic reforming is higher than the reforming without porous ceramic. The further detailed catalyst supported with porous ceramic for biogas and tar reforming will be investigated in future.

Fig. 9 presents the comparison of gas composition in the two modes, that is, with and without porous ceramic reforming. The gas concentration of hydrogen for porous ceramic reforming is higher than the one which is filled nothing in the reformer. The maximum H₂ concentration was found at the higher value 60.59% for porous ceramic reforming than the value 43.37% for without porous ceramic reforming

Table 7 – Experimental results of different steam/biomass ratio without porous ceramic reforming

Steam to biomass ratio	1.05	2.05	2.53	3.47
Reactor temperature (°C)	850	850	850	850
Wet feed rate (kg/h)	0.48	0.48	0.48	0.48
Dry feed rate (kg/h)	0.44	0.44	0.44	0.44
Steam rate (kg/h)	0.5	0.98	1.21	1.66
Gas density (kg/Nm ³)	0.69	0.72	0.73	0.73
Gas yield (m ³ /kg daf biomass)	2.12	2.27	2.33	2.06
Low heating value (MJ/Nm ³)	13.40	12.89	12.87	12.67
Residence time (s) at reactor temperature	7.25	4.87	4.07	3.53
Hydrogen yield (g H ₂ /kg biomass, dry basis)	82.35	84.93	86.08	75.41

at the $S/B = 3.47$, and has a largest increase of 39.68%. CO and CH₄ concentrations for porous ceramic reforming are shown below without porous ceramic reforming at all values of S/B . The LHV of producer gas decreased from 13.40 to 12.67 MJ/Nm³ with the increase of S/B value. The reduced residence time at reactor temperature is presented in Table 7, and the decreasing trend is similar with the tests varying S/B for porous ceramic reforming.

4. Conclusions

In this research, an experimental investigation of an updraft biomass gasifier combined with a porous ceramic reformer is conducted using pine sawdust under various operating conditions, producing a hydrogen-rich syngas with a high calorific value in the range of 8.10–13.40 MJ/Nm³ and the hydrogen yield in the range of 45.05–135.40 g H₂/kg biomass.

The gasification temperature was found to affect the hydrogen yield strongly. Higher temperature favors hydrogen production. Tests showed increasing hydrogen yield with increasing gasifier temperature varying from 74.84 g H₂/kg biomass at reaction temperature of 800 °C to 135.4 g H₂/kg biomass at a gasifier temperature of 950 °C.

Higher equivalence ratio increased the temperature of reaction zone, as a cost, the quality of producer gas declined due to more H₂ and CO were consumed. In tests, equivalence ratio varies from 45.05 g H₂/kg biomass at an equivalence ratio of 0.30 to 99.55 g H₂/kg biomass at an equivalence ratio of 0.0, irrespectively. An optimum value of ER was found to be 0.05 in this study.

The steam/biomass ratio was also observed in the research. The tests showed that the increasing value of steam/biomass ratio corresponding with an increase in hydrogen concentration. The increment of hydrogen yield was shown from 77.99 to 95.89 g H₂/kg biomass in the range of steam/biomass ratio from 1.05 to 3.47. According to the hydrogen yield and energy aspects, a steam/biomass ratio was found as the optimum in the steam gasification.

The effect of porous ceramic reforming was studied. The distinct difference of tar component, in the porous ceramic reforming, was the water-soluble tar. The hydrogen composition with porous ceramic reforming is higher than that without porous ceramic filled in reformer.

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