



# A novel reforming method for hydrogen production from biomass steam gasification

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## ABSTRACT

In this work, an experimental study of biomass gasification in different operation conditions has been carried out in an updraft gasifier combined with a porous ceramic reformer. The effects of gasifier temperature, steam to biomass ratio (S/B), and reforming temperature on the gas characteristic parameters were investigated with and without porous ceramic filled in reformer. The results indicated that considerable synergistic effects were observed as the porous ceramic was filled in reformer leading to an increase in the hydrogen production. With the increasing gasifier temperature varying from 800 to 950 °C, hydrogen yield increased from 49.97 to 79.91 g H<sub>2</sub>/kg biomass. Steam/biomass ratio of 2.05 seemed to be optimal in all steam-gasification runs. The effect of reforming temperature for water-soluble tar produced in porous ceramic reforming was also investigated, and it was found that the conversion ratio of total organic carbon (TOC) contents is between 71.08% and 75.74%.

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## 1. Introduction

Hydrogen is regarded as the energy for future with its cleanness and high calorific value and has become a focus of renewed interest in many parts of the world. In present, most of hydrogen is generated in large scale from natural and fossil fuels via steam methane reforming (MSR) and coal gasification (Basile et al., 2008; Saxena et al., 2008). These production pathways are not an environmentally clean and economically viable solution and result in significant CO<sub>2</sub> emissions. As a source of renewable energy, biomass energy has significant environmental benefits including lower emissions of carbon dioxide and other greenhouse gases. So, biomass has been considered as one of the most probable source for hydrogen production. Thermochemical biomass gasification has considerable potential with respect to product renewable hydrogen (Florin and Harris 2007).

Most researchers carried out experiments of hydrogen production with batch-type reactors (González et al., 2008; Hanaoka et al., 2005; Yang et al., 2006), circulating fluidized bed reactors (Li et al., 2004; Swierczynski et al., 2008) and bubbling fluidized bed reactors (Franco et al., 2003; Lv et al., 2004; Rapagnà et al., 2000). Their studies generally included a main reactor and a gas and tar collecting system. However, some problems were found in these researches: lower hydrogen production and severe tar and char formation. To solve these problems, catalytic treatments as common ways are proposed to reduce tar content in bio-gas and catalysts could be used to effectively eliminate tar in biomass

gasification process (Shen et al., 2008). A lot of researchers developed different secondary reformers which followed a gasifier. The reforming of syngas and tar include three methods from a reaction point of view, that is steam reforming, catalyst reforming and CO<sub>2</sub> reforming (Chun et al., 2008). Czernik et al. (2007) proposed a two-step process that started with fast biomass pyrolysis followed by catalytic steam reforming of bio-oil to produce hydrogen. Five catalysts including a Ni-based commercial catalyst, C11-NK, for reforming naphtha and four laboratory formulations were tested to investigate hydrogen yields obtained in a bench-scale fluidized bed. Through adding a CO-shift reactor downstream from a bubbling fluidized bed biomass gasifier and a steam reforming catalytic reactor, Corella et al. (2008) found about equivalent to 140 g H<sub>2</sub>/kg biomass, daf basis was generated from exit gas. Some catalysts such as Rh/CeO<sub>2</sub>/SiO<sub>2</sub> (Tomishige et al., 2004), Ni/CeO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> (Nishikawa et al., 2008), were used to study the effect of reforming of tar cracking. Chun et al. (2008) investigated the reforming characteristics and optimum operating conditions of the plasmatron-assisted CH<sub>4</sub>-reforming reaction for the hydrogen-rich gas production. Wang et al. (1998) presented model compounds and the aqueous fraction of poplar oil with nicked-based steam-reforming catalyst at a bench-scale reactor. Rapagnà et al. (2000) investigated catalytic biomass steam gasification in a bench-scale plant consisting of a fluidized bed gasifier and a secondary catalytic fixed-bed reactor. A novel catalytic candle filter was proposed by Draelants et al. (2001), Engelen et al. (2003), and Zhao et al. (2000) to integrate the high-temperature removal of particles and tars from biomass gasification gas in a one-step gas-cleaning process. Different catalytic filter discs were prepared according to different procedures and containing Ni and CaO

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loadings. Recently, Corella et al. (2004) employed nickel-based monoliths for tar elimination in fuel gas produced by biomass gasification in a fluidized bed at a small pilot-plant scale.

These researches were mainly carried out reforming of tar or syngas with different catalysts. However, these methods encountered some technological limitations and economical constraining factors, for example, the tar produced from biomass gasification process leads to severe deactivation of conventional catalysts, the expensive cost of noble metals catalyst such as Pt, Pd, Rh and Ru and the serious reducing catalysts life due to the fouling by carbon build-up on the surface of the catalyst itself (Rapagnà et al., 1998). Although some catalysts do have better effect on bio-gas reforming and tar removal, most of them were used in biomass sequencing batch feeding manners (Asadullah et al., 2002; Li et al., 2008; Mahishi and Goswami, 2007; Zhao et al., 2000). As the great difference between sequencing batch feeding matter and continuous one, and in practice, the bio-gas produced from continuous feeding type contains much impurities such as tars, chars, some carbon black and ashes, these materials might fouling catalyst surface and cause catalyst deactivated. So, the practicability of catalysts used in practical biomass continuous feeding gasification might be doubted.

In this paper, a novel reformer combined with continuous biomass steam gasification was proposed to reform producer gas and crack tars, in which a porous ceramic rather than any catalyst was filled inside the secondary reformer. The properties of heating regenerative and internal surface area rather than catalysts came from ceramic composition were utilized to improve steam reforming and tars cracking process.

## 2. Experimental

The original material (pine sawdust) used as the feedstock for gasification was obtained from a timber mill in Dalian City, China.

**Table 1**  
Proximate analysis and ultimate analysis of pine sawdust.

Proximate analysis (w/w% dry basis)	Ultimate analysis (w/w% dry basis)		
Fixed carbon	18.88	C	44.75
Volatile	76.85	H	6.31
Ash	0.34	O <sup>a</sup>	46.87
		N	1.68
Moisture content (w/w% wet basis)	3.93	S	0.05
Higher heating value (MJ/kg)	18.47	Ash	0.34

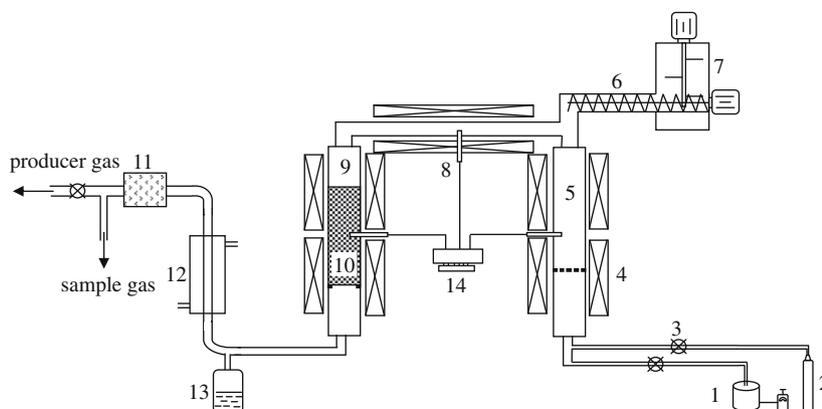
<sup>a</sup> Calculated by difference.

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 oxygen (O) obtained 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 reforming. 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, where heating regenerative can be defined as the specific heat divided by heat conduction coefficient, that is  $c_p/\lambda$ . 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. Steam of 120 °C generated in an electrical heated boiler was employed as gasification agents, 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 feeder and a variable speed motor. The gasifier and the reformer were pre-heated 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



**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. thermo-couple; 9. secondary reformer; 10. porous ceramic layer; 11. purification and drying device; 12. condenser 13. tar collector; and 14. PID temperature controller.

**Table 2**

The chemical composition and physical properties of porous ceramic.

Chemical composition (wt.%)		Physical properties	
SiO <sub>2</sub>	26	Density $\rho$ (kg/m <sup>3</sup> )	2100
Al <sub>2</sub> O <sub>3</sub>	60	Specific heat $c_p$ (J/(kg K))	850–1050
MgO	11	Softening temperature $T_s$ (°C)	1600
Fe <sub>2</sub> O <sub>3</sub>	1	Heat conduction coefficient $\lambda$ (20–1000 °C, W/(m K))	1.4–2
Na <sub>2</sub> O + K <sub>2</sub> O + CaO	1.1–1.5	Heating regenerative $c_p/\lambda$ (m s/kg)	425–750
TiO <sub>2</sub> + BaO + NiO	0.8	Thickness of wall $d$ (mm)	0.45
		Porosity $\phi$ (%)	80
		Surface area $A$ (m <sup>2</sup> /m <sup>3</sup> )	805

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 45 min.

Products (gas and liquids) exiting the gasifier passed through 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 set up. 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<sub>2</sub> for the sake of steam removal and gas purity. Gases were collected using a gas-bag only after 10 min of gasification.

The product gas was collected periodically through a gas syringe and analyzed off-line by gas chromatograph (GC). The gas fraction composition, mainly H<sub>2</sub>, CO, CH<sub>4</sub>, CO<sub>2</sub> and C<sub>2</sub>–C<sub>3</sub> 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<sub>2</sub>, O<sub>2</sub>, N<sub>2</sub>, CO, CH<sub>4</sub> concentrations; the second column is TDX-01 yielded CO<sub>2</sub> concentration, the third column is GDX-102 chromatographic column as it was used for C<sub>2</sub>–C<sub>3</sub> 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-VCPH, Japan). The surface morphology of the porous ceramic before and after reforming reaction was observed by scanning electron microscopy (SEM) using KYKY-2800B (KYKY technology development LTD) microscope with an accelerating voltage of 15 kV.

### 3. Results and discussion

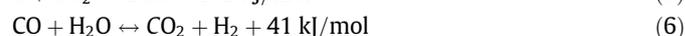
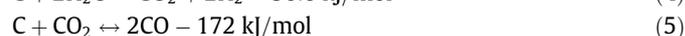
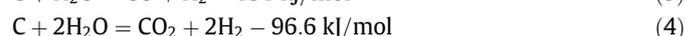
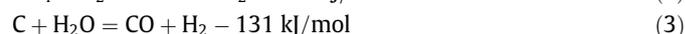
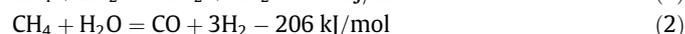
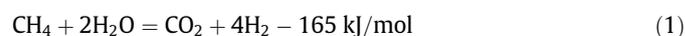
The effects of reactor temperature, steam to biomass ratio and reforming temperature on the hydrogen production were studied. And the comparison of reforming with or without porous ceramic reforming results was also investigated.

#### 3.1. Effect of reactor temperature

The reactor temperature is one of the most important operating variables for biomass gasification. In present work, reactions were performed at four reactor temperatures from 800 to 950 in 50 °C increments. Fig. 2a shows the effects of reactor temperature on product distributions from pine sawdust at S/B mass ratio of 1.05 and keeping the temperature of porous ceramic reformer at 800 °C.

From Fig. 2a, it can be seen that the concentration of H<sub>2</sub> exhibits an increasing trend with temperature without secondary reform-

ing, while the obvious increase of H<sub>2</sub> is observed in the process of porous ceramic reforming. Because the reactions of H<sub>2</sub> production are endothermic process, reaction temperature strongly influences the yield of H<sub>2</sub>. As porous ceramic was used to reform producer gas, reactions Eqs. (1)–(5) might be strengthened, as a result, the H<sub>2</sub> concentration has a great increase in whole range of temperature. In addition, due to the tars in the producer gas might be cracked with reaction (7) in porous ceramic, heavy oil vapours, C<sub>1</sub>–C<sub>5</sub> hydrocarbons, naphthalin, gas oils and aromatic compounds were decomposed to yield a mixture of small mole gases (H<sub>2</sub>, CO, CO<sub>2</sub>). The concentration of CO has a slight increase with porous ceramic reforming but it is below the one without reforming process. Under porous ceramic reforming, reactions (2), (3), (5), (6), and (7) were enhanced for the sufficient contact in the straight pores embedded in ceramic. The concentration of CH<sub>4</sub> also has a great decrease after porous ceramic reforming. Endothermic reactions (1) and (2) have mainly influence on CH<sub>4</sub> conversion and in the effect of the heating regenerative of porous ceramic, compared to without reforming, the concentration of CH<sub>4</sub> decreased clearly through the reforming process



Steam porous ceramic reforming of tars

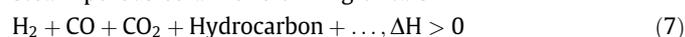


Fig. 2b shows the change of H<sub>2</sub>/CO and CO/CO<sub>2</sub> molar ratios in the product gas of porous ceramic reforming with reactor temperature. The molar ratio of H<sub>2</sub>/CO of producer gas which value varied between 1 and 2 (1 < H<sub>2</sub>/CO < 2) could be useful for chemical syntheses, e.g. methanol, pure naphtha production, Fisher Tropsh (F-T) syntheses (ratio about 2.0) and oxo-synthesis (ratio about 1.0) processes (Song and Guo, 2006; Skoulou et al., 2008) etc. In present work, as H<sub>2</sub> concentration has a slight increasing trend in the range of 800–950 °C, however, CO concentration increased gradually in the range of 800–900 °C, and decrease in higher temperature range. Then, the calculated ratio of H<sub>2</sub>/CO shows first decrease and then increase with temperature, which varied between 1.74 and 2.02. While CO/CO<sub>2</sub> ratios (between 1.33 and 1.64) increased as CO concentration was always higher than CO<sub>2</sub> content with temperature for the all range of values tested.

The experimental results were shown in Table 3, hydrogen yield increased from 49.97 to 79.91 g H<sub>2</sub>/kg biomass in the range of reaction temperature from 800 to 950 °C, while the low heating value (LHV) varied between 11.62 and 12.08 MJ/Nm<sup>3</sup>. Residence time is defined as the total reactor volume divided by the volumetric flow rate of producer gas under same operation conditions. As shown in Table 3, residence time decreased from 6.4 to 4.5 s in whole range

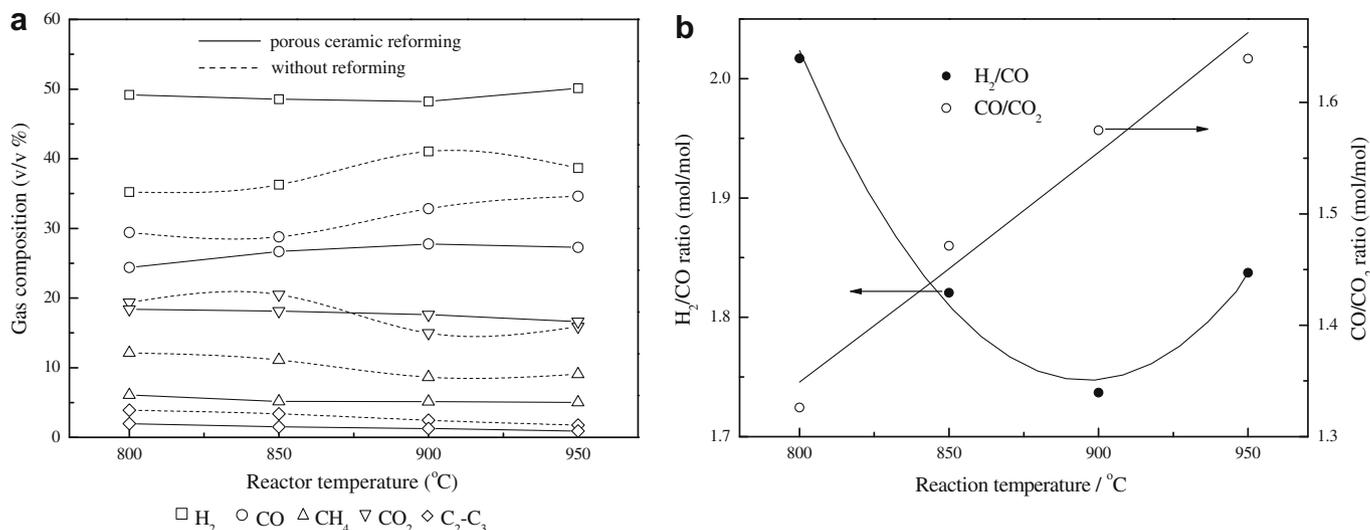


Fig. 2. Effect of reactor temperature on gas composition (a) and H<sub>2</sub>/CO and CO/CO<sub>2</sub> molar ratio (b).

Table 3

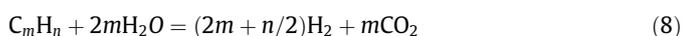
Experimental result of different reactor temperatures.

Reactor temperature (°C)	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
Reforming temperature (°C)	800	800	800	800
Gas density (kg/Nm <sup>3</sup> )	0.64	0.65	0.65	0.63
Gas yield (m <sup>3</sup> /kg daf biomass)	1.07	1.34	1.50	1.72
Hydrogen yield (g H <sub>2</sub> /kg biomass, dry basis)	49.97	58.09	64.49	79.91
Low heating value (MJ/Nm <sup>3</sup> )	12.08	11.66	11.62	11.73
Residence time (s)	6.40	5.58	5.04	4.50

of increase reaction temperature. It could be inferred partly that higher reaction temperature caused large gas yields produced from biomass.

### 3.2. Effect of steam/biomass ratio

The effect of steam/biomass ratio (S/B) has been studied over the range 1.05–2.53 at the gasifier temperature of 850 °C and keeping reforming temperature at 800 °C. As a comparison, the product gas concentrations without and with porous ceramic reforming were shown in Fig. 3. With porous ceramic reforming, hydrogen has a slight increase from 48% to 51%, it is far higher than without reforming process one which only shows the concentration from 36% to 39%. The maximum concentration increase ( $\Delta H_2$ ) reaches 41% at the S/B of 1.4. It is clear that the reaction of hydrogen conversion mainly depends on reactions 1, 2, 3, 4, 5, and (7) in the porous ceramic reforming. Not only the tars or heavier hydrocarbons were reformed but the carbon black trapped in the surface of ceramic pores could be reacted with steam and increase the hydrogen production. Carbon monoxide, methane, carbon dioxide and C<sub>2</sub>–C<sub>3</sub> concentrations have a significant decrease with porous ceramic reforming compared to without one, which were maximum decrease ( $\Delta CO$ ,  $\Delta CH_4$ ,  $\Delta CO_2$ , and  $\Delta(C_2-C_3)$ ) of 22%, 55%, 26% and 62%, respectively. The results suggest that porous ceramic reforming is favor for the hydrocarbons conversion with reactions (1), (2), (7), and (8)



The value of H<sub>2</sub>/CO and CO/CO<sub>2</sub> molar ratio for porous ceramic reforming in the fixed-bed gasifier was analyzed. The change of

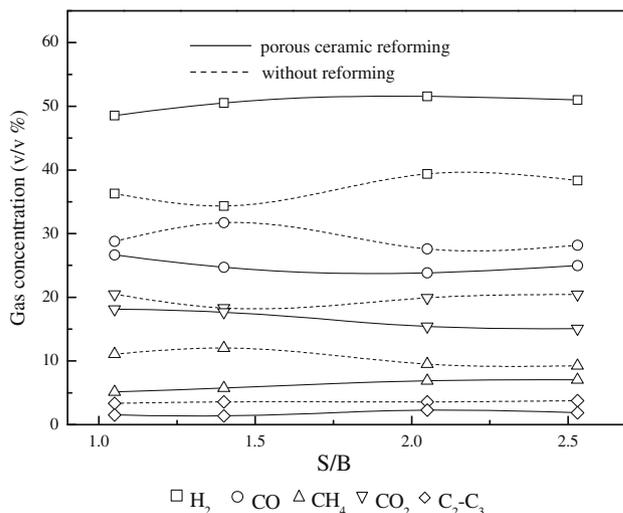


Fig. 3. Effect of steam/biomass ratio on gas composition.

H<sub>2</sub>/CO has a slight decrease with the increasing S/B ratio, which varied between 2.03 and 2.16, while the ratio of CO/CO<sub>2</sub> shows an increase trend because of higher CO concentration which changed from 1.21 to 1.66, which indicates that higher S/B value produce an enrich CO syngas. A maximum mole ratio of H<sub>2</sub>/CO was observed being S/B ratio of 2.05. Combined the change of hydrogen concentration in Fig. 3, it could be concluded that too large of S/B ratio is not always favor to the hydrogen production. From the view of energy, the excess steam would consume plenty of heat in the process of reaction and the separation of product gas from steam condensation and dryness. Therefore, there is an optimal S/B ratio existed in all runs, 2.05 might be the optimal value in present work.

Table 4 shows the experimental results of different steam/biomass ratio with porous ceramic reforming. Gas yields increase linearly with the increase of S/B ratio, from 0.89 to 1.14 Nm<sup>3</sup>/kg daf biomass. The desired results indicate that steam promote tar and char reduction (Wei et al., 2006). Tar cracking, steam reforming and char gasification might be the main conversion patterns of the increased gas yield. Moreover, the larger contact area and good heating regenerative of porous ceramic enhanced this reforming process. Considering the concentration of H<sub>2</sub>, a similar uptrend of

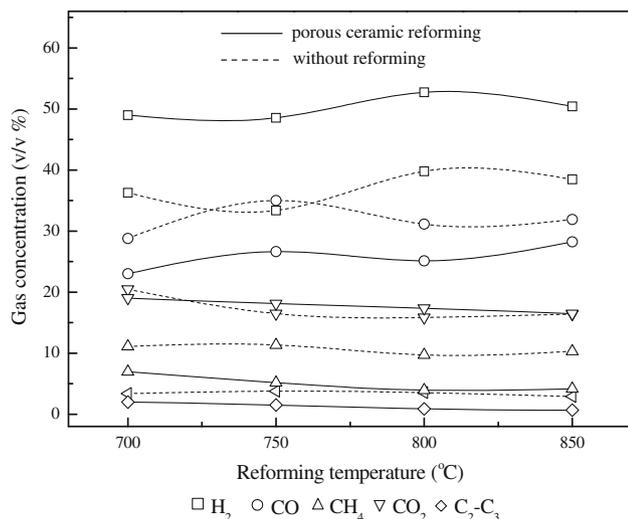
**Table 4**  
Experimental result of different steam/biomass ratios.

Steam to biomass ratio	1.05	1.4	2.05	2.53
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	0.67	0.98	1.21
Reforming temperature (°C)	800	800	800	800
Gas density (kg/Nm <sup>3</sup> )	0.64	0.62	0.60	0.60
Gas yield (m <sup>3</sup> /kg daf biomass)	0.89	0.99	1.07	1.14
Hydrogen yield (g H <sub>2</sub> /kg biomass, dry basis)	39.03	44.91	49.22	51.72
Low heating value (MJ/Nm <sup>3</sup> )	12.22	12.31	12.54	12.62
Residence time (s)	5.30	6.47	6.25	6.07

hydrogen yields was presented from 39.03 to 51.72 g H<sub>2</sub>/kg biomass in Table 4. As the concentration of H<sub>2</sub> and CO obvious contribution, the values of LHV increase with S/B ratio, which varied in the range of 12.22–12.62 MJ/Nm<sup>3</sup>.

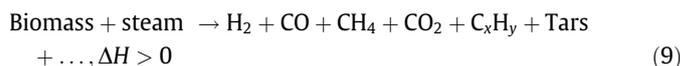
### 3.3. Effect of reforming temperature

In this paper, experiments were performed by steam gasifying pine sawdust through controlling the temperature of porous ceramic reformer (see Fig. 4). The fixed-bed gasifier was maintained at the same temperature, 850 °C. The steam to biomass ratio was maintained at one for all the experiments. The temperature of reformer was changed over the range from 700 to 850 °C in 50 °C increments. Compared to the results without reforming process, it was observed that the concentration of hydrogen greatly increased with porous ceramic reforming. The hydrogen content had increased by 35.0% (from 36.3% to 49.0%), 45.4% (from 33.4% to 48.5%), 32.6% (from 39.8% to 52.7%) and 31.0% (from 38.5% to 50.4%) at four reforming temperatures of 700, 750, 800 and 850 °C, respectively. The higher reforming temperature favors to hydrogen production. Although three ways H<sub>2</sub> is generated in the product gas are mentioned above, porous ceramic reforming process might take an important role on the hydrogen production. A series of complex endothermic and exothermic reactions happened in reforming process and these reactions were coupled each other simultaneously to influence the gas composition, specially to hydrogen. So, from Fig. 4, it also can be inferred that there is an optimum value of reforming temperature in reforming process, here, 800 °C could be the right value. Other gas such as CO, CH<sub>4</sub>,



**Fig. 4.** Effect of reformer temperature on gas composition.

CO<sub>2</sub> and C<sub>2</sub>–C<sub>3</sub> also decrease on comparison without reforming process



The trends of H<sub>2</sub>/CO and CO/CO<sub>2</sub> molar ratio of product gas with reforming temperature also were calculated. With reforming temperature increase, the molar ratio of H<sub>2</sub>/CO varied between 1.79 and 2.13 (1.79 < H<sub>2</sub>/CO < 2.13). The molar ratio of CO/CO<sub>2</sub> shows a rough increase trend with temperature increase, which changed from 1.21 to 1.71 (1.21 < CO/CO<sub>2</sub> < 1.71). Table 5 shows the experimental results under different reformer temperatures. Gas yields increased from 0.99 to 1.69 m<sup>3</sup>/kg daf biomass with increase reforming temperature. Accordingly, hydrogen yields varied from 43.13 to 76.37 g H<sub>2</sub>/kg biomass due to the increase of H<sub>2</sub> concentration.

Many researchers had used catalyst in secondary reformer to reform cleaned bio-gas which was removed the char, ash tars and other impurity materials (Mahishi and Goswami, 2007), it is different that this paper used porous ceramic other than any catalysts for tars cracking, raw bio-gas reforming and enhancing of hydrogen yield. In fact, the chemical composition of ceramic include some metal oxides such as MgO, Fe<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, K<sub>2</sub>O, CaO, TiO<sub>2</sub> and BaO etc. (see in Table 2). These metal oxides might play catalyst or support roles (Alarcón et al., 2004; Cerfontain et al., 1987; Ersolmaz and Falconer, 1986; Furusawa et al., 2007; Takenaka et al., 2004; Wiltowski et al., 2008; Zhu et al., 2000) in the steam reforming reaction and hydrocarbon or tar cracking, which enhanced H<sub>2</sub> production. Although the carbon black could foul the surface of ceramic pores and cause these catalysts reactivation, it has little effect on producer gas reforming. This is because that the key roles of porous ceramic playing are its good heating regenerative and large internal surface area rather than the catalysts itself came from ceramic composition. And these physical properties might propel the process of hydrogen conversion and tars removal. So the hydrogen yield with porous ceramic reforming is higher than no reforming one. The value of LHV varied in the range between 11.66 and 22.26 MJ/Nm<sup>3</sup>.

In general, the tars produced in biomass gasification process include two parts, the tar in the organic phase and soluble tar. The former is not or difficult to dissolve in water and the later is dissolved in water phase easier. The organic phase tar can be weighted after separated from the mixture condensate and the soluble tar can be measured with total organic carbon (TOC) analysis. In this work, as the tar in organic phase is too little to be separated and measured, only soluble tar in water phase was measured by TOC analyzer. Table 6 shows the content of TC (total carbon), TOC and IC (inorganic carbon) in soluble tar with and without porous ceramic reforming. As can be seen, the content of TOC in tars varied between 2010 and 2675 mg/l without porous ceramic reforming. However, expecting results were obtained that the

**Table 5**  
Experimental result of different reformer temperatures.

Reforming temperature (°C)	700	750	800	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
Reactor temperature (°C)	850	850	850	850
Gas density (kg/Nm <sup>3</sup> )	0.64	0.65	0.61	0.63
Gas yield (m <sup>3</sup> /kg daf biomass)	0.99	1.34	1.44	1.69
Hydrogen yield (g H <sub>2</sub> /kg biomass, dry basis)	43.13	58.09	67.88	76.37
Low heating value (MJ/Nm <sup>3</sup> )	12.22	11.66	22.26	21.79
Residence time (s)	6.64	5.58	5.23	4.63

**Table 6**

The comparison of TC, TOC and IC at different reformer temperatures.

Reactor temperature (°C)	Without porous ceramic reforming			Porous ceramic reforming			TOC conversion (%)
	TC/mg/l	TOC/mg/l	IC/mg/l	TC/mg/l	TOC/mg/l	IC/mg/l	
700	2807	2675	133.5	899.1	766.9	132.2	71.08
750	2755	2506	247.9	806.5	699.4	107.1	72.09
800	2500	2348	150.8	664.4	569.7	95.0	75.74
850	2097	2010	86.3	610.5	528.8	81.7	73.69

content of TOC in tars reduced between 528.8 and 766.9 mg/l using porous ceramic as filler. The conversion of TOC is roughly between 71.08% and 75.74% in the two types of reforming process. This result revealed that, (1) tars cracking might favor higher reforming temperature and, (2) the porous ceramic reformer take promoter role in tar cracking process. To a great extent, porous ceramic reforming not only, avoids the organic phase tar production but also has not the problem of deactivation like using catalyst for reforming encountered.

The surface morphology of the porous ceramic was also investigated by scanning electron microscopy (SEM). At a magnification of 5000 $\times$ , the virgin porous ceramic had clear, uniform surfaces, whereas after reforming striations were seen along the dirty and ambiguity surface. It could be observed clearly from SEM image of virgin porous ceramic surface is pure and almost has not any other impurity. The ceramic surface distributes much solid pores which were formed in manufacture process. However, it was observed that there were many granular particles covering the surface of used porous ceramic. Actually, in the reforming process, tars, carbon blacks and ashes produced from biomass steam gasification were trapped easily by the straight pores embedded in ceramic, and the granular particles are these substances. Compared with virgin porous ceramic, the surface of after reforming one was covered completely. However, unlike catalyst exists the limitation of deactivate, it was not found apparently that this drawback happened for reforming process. Although the carbon black trapped on the surface of ceramic pores has not effect on the reforming process, the removal of carbon black would be recommended for further study by using partial oxidation or other methods.

#### 4. Conclusions

Steam gasification experiments of pine sawdust were performed in a continuous feeding fixed-bed with a porous ceramic reformer. A medium level LHV gas was produced in the range of 11.62–22.26 MJ/Nm<sup>3</sup>. A high ratio of H<sub>2</sub>/CO, ranging between 1.74 and 2.16, can be obtained from product gas porous ceramic reforming. In all cases, the hydrogen concentration shows a clearly increase compared with no reforming process.

The rise temperature favors to the hydrogen production, while higher temperature has a slight low of LHV of product gas. Steam/biomass ratio was observed as an effect factor to biomass gasification. Too higher S/B ratio might not the optimum selection, in this paper, 2.05 might be the optimal value. With S/B ratio rise, steam reforming was enhanced and TOC content decreased obviously. In addition, reforming temperature showed an important influence on the H<sub>2</sub> production and tars removal. On comparison with no reforming process, the maximum hydrogen content had increased by 45.4% at 800 °C, and the content of TOC dropped from 2348 to 569.7 mg/l.

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